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As man modifies watersheds by removal of natural vegetation and stream channelization, disequilibria in both the terrestrial and aquatic environments result. These disequilibria are the major problem in controlling sediments and nutrients from nonpoint sources and improving the quality of the stream biota.

In this report we review the literature dealing with (1) the possible use of near stream vegetation to reduce the transport of sediment and nutrients from the terrestrial to the aquatic environment and decrease stream temperature fluctuations, (2) the effect of stream morphology on sediment transport, and (3) how near stream vegetation and stream morphology affect the biota of streams. The results of this review suggest proper management of near-stream vegetation and channel morphology can lead to significant improvements in both the water and biological quality of many streams. However, critical research outlined in this report is still necessary if we are to properly use this management alternative to attain the objectives of the Federal Water Pollution Control Act of 1972 (Public Law 92-500).

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IMPACT OF NEARSTREAM VEGETATION AND STREAM MORPHOLOGY ON WATER QUALITY AND STREAM BIOTA

UNITED STATES · ENVIRONMENTAL PROTECTION AGENCY ·

Environmental Research Laboratory
Office of Research and Development
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August 1977

IMPACT OF NEARSTREAM VEGETATION AND STREAM MORPHOLOGY ON WATER QUALITY AND STREAM BIOTA

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FOREWORD

As environmental controls become more costly to implement and the penalties of judgment errors become more severe, environmental quality management requires more efficient analytical tools based on greater knowledge of the environmental phenomena to be managed. The development of management or engineering tools to help pollution control officials achieve water quality goals through watershed management is an integral part of this Laboratory's research on the occurrence, movement, transformation, impact, and control of environmental contaminants.

Water quality in streams receiving pollution from nonpoint sources is of great concern to EPA. Through the literature review presented in this report, gaps in scientific knowledge of the ways in which nearstream vegetation and stream morphology affect water quality and of the manner in which NPS pollution affects stream biota are identified. Particular stress is given to the beneficial use of greenbelts, but important questions are raised concerning their effectiveness in controlling NPS pollution from agricultural lands. In addition, the review suggests research to be accomplished prior to the adoption of rational management strategies to effectively control water pollution in streams receiving NPS pollutants, which should be of particular interest to persons in a wide variety of disciplines.

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PREFACE

We have attempted a synthesis of research from several fields to evaluate the effects of nearstream vegetation and channel morphology on water quality and stream biota in agricultural watersheds. An inevitable result of such a synthesis is inadequate coverage of the literature from each field. We acknowledge this deficiency and solicit comments on weaknesses in our coverage. However, we are less concerned about further references supporting our suggestions than about references which add new perspectives or disagree with our conclusions. Since our goals are wise use of biological, soil, and water resources, we hope readers will bring relevant studies to our attention. (A glossary is included (p. 85-90) for readers unfamiliar with the terminology of all fields discussed in this report.)

From our perspective a major problem in the effort to control non-point sediment pollution is the common philosophy that it is an agricultural problem. This is an error on two counts. First, not all sediment pollution derives from agricultural activities and second, fields other than agriculture, including agricultural engineering, have expertise which should be brought to bear on sediment pollution problems. The two problems are only indirectly related. The long-term objective of improved water quality can best be served with multi-disciplinary efforts which transcend the classical disciplines, such as agriculture, engineering, and ecology. We are particularly concerned that more thought be given early in the planning phase of projects to the long-term ecological consequences of management alternatives. Water quality degradation can be reversed if the past emphasis on control of soil erosion is supplemented with a broader approach to water quality problems.

An early draft of this paper was read by a number of scientists from many backgrounds. The most intriguing comments came from a biologist and from an agriculturist. One suggested that we attempted to generalize too broadly; that is, since most of our examples come from midwestern situations we should, perhaps, explicitly state that our conclusions might apply only to that region. Another individual commented that the general principles might apply to some regions but they probably could not be used in the high intensity agriculture of central Illinois. These comments illustrate the problems which result from differing perspectives. In addition, they are related to the problems involved in defining areas of applicability. For example, do our discussions pertain to highly modified agricultural drains, to natural stream channels, to drains and channels of specific sizes, or to all of these? We feel they apply primarily to headwater streams in most watersheds, but as we hope to demonstrate in this review, definitive answers to these questions are not available. That is an alarming statement after decades of research effort. Rigorous scientific investigations addressing the problems posed in this report are long overdue.

ABSTRACT

Like all functional parts of landscape units, streams have dynamic equilibria in nutrient and sediment loads and biota. As man modifies watersheds by removal of natural vegetation and stream channelization, disequilibria in both the terrestrial and aquatic environments result. These disequilibria are the major problem in controlling sediments and nutrients from non-point sources and improving the quality of the stream biota. Unfortunately, most attempts to control non-point pollutants in agricultural watersheds emphasize reestablishing the terrestrial equilibrium via tillage practices such as minimum tillage, winter crop cover, and terraces. These efforts, which depend on erosion control as measured by the Universal Soil Loss Equation, utilize technologies for preserving soil productivity. This approach must be replaced by one in which improvement in water quality and quality of the stream biota is a primary objective. This requires erosion control on the general landscape plus an increased understanding of the link between terrestrial and aquatic systems and the effect of stream morphology on the dynamics of sediment transport and quality of the stream biota.

In this report we review the literature dealing with (1) the possible use of near stream vegetation to reduce the transport of sediment and nutrients from the terrestrial to the aquatic environment and decrease stream temperature fluctuations, (2) the effect of stream morphology on sediment transport, and (3) how near stream vegetation and stream morphology affect the biota of streams. The results of this review suggest proper management of near-stream vegetation and channel morphology can lead to significant improvements in both the water and biological quality of many streams. However, critical research outlined in this report is still necessary if we are to properly use this management alternative to attain the objectives of the Federal Water Pollution Control Act of 1972 (Public Law 92-500).

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SECTION 1

INTRODUCTION

Sediments are largely non-point sources of pollution. Because of this diffuse nature, erosion and sediment control methods are inherently more complex than those used to control point sources of pollution and will probably involve several control strategies acting synergistically. The Environmental Protection Agency and the United States Department of Agriculture have suggested several feasible methods of control which should be investigated (Agricultural Research Service 1975, 1976, Becker and Mills 1972). These methods can generally be divided into two broad classes: (1) those which attempt to prevent erosion from occurring, i.e. minimum tillage, winter crop cover, terraces and other soil conservation practices and (2) those which attempt to prevent the sediment from entering streams once erosion has occurred.

Early conservation efforts emphasized soil erosion prevention (1 above) with little emphasis on maintenance of water quality. Incorporation of water quality as another objective of conservation practices represents a major shift in conservation policy. To meet the water quality standards set for 1983 by the federal government an even broader perspective will have to be established, including more detailed understanding of (1) the link between terrestrial ecosystems and water quality and (2) the dynamics of sediment and nutrient transport within streams. This increasing breadth of perspective requires a more demanding synthesis of several bodies of knowledge, including hydraulic engineering, geology, the study of stream morphology and dynamics, and terrestrial and aquatic ecology.

We do not suggest that past management efforts have been in vain. Rather our main point is that continued efforts to stabilize the terrestrial environment (minimum tillage, rotational practices, etc.) must be supplemented with improved management of in and near channel areas before significant improvements in water quality and quality of the stream biota will occur. Furthermore, there is a serious deficiency in our knowledge of the dynamics of in and near channel characteristics. Hopefully, this report will stimulate research addressed to the solution of land-water resource problems.

In this report we evaluate (1) existing data regarding the ability of vegetation to act as a nutrient and sediment filter, (2) the effects of stream morphology on water quality, (3) the effects of streamside vegetation on water temperature, and (4) the potential impact of greenbelts (a combination of nearstream vegetation and stream morphology) on stream biota and their possible uses for other recreational activities. We then use this information to judge the feasibility of using greenbelts for improving water quality and quality of the stream biota. Finally, we propose several major questions which must be addressed before the social and economic benefits of greenbelts can be fully evaluated.

SECTION 2

CONCLUSIONS

1. Vegetation as a Nutrient Filter.

   a. Past efforts to use vegetation to filter nutrients in solution from surface runoff have yielded conflicting results. The reasons for this variability are largely unknown due to poorly controlled experiments. Important variables include type of vegetation, detention time, volume of water treated, and soil type.

   b. Conflicting data exists regarding the importance of subsurface inputs of phosphorus into streams. The magnitude of subsurface inputs appears to be primarily related to the quality of the tile line and the presence of surface intakes.

   c. Nearly all of the phosphorus (greater than 85%) and most of the nitrogen (greater than 70%) in surface runoff is attached to sediment.

   d. Nutrients are usually absorbed to the smaller-sized particles, especially the clay fraction. Hence, removal of nutrients from surface runoff by vegetation will be achieved primarily by removing the sediments to which the nutrients are attached.

2. Vegetation as a Sediment Filter.

   a. Recent data from Black Creek watershed in Indiana indicates the major fraction of sediment loss in an agricultural watershed is via surface flow. Therefore, sediment inputs into streams can be controlled by adequate treatment of surface runoff.

   b. Data from field and laboratory studies in forestry and agriculture indicate vegetation can effectively filter sediment from both sheet and shallow channel flow. Sediment reduction is less likely during channel flow exceeding the height of herbaceous vegetation. Several variables appear to act in an interrelated manner to determine the effectiveness of vegetation filters. These include filter length, slope of the filter, vegetation characteristics, size distribution of the incoming sediments, degree of submergence of the filter, application rate of the water to be filtered, and initial concentration of the sediment.

   c. The placement of a vegetative filter and the width or length of the filter required to remove a given fraction of the incoming sediment and the duration of its effectiveness is dependent on the interaction of physical factors, biological factors, and the specifications of water quality, all of which are yet to be thoroughly evaluated under normal agricultural conditions and quantitatively related to each other in any predictive manner.

3. Effect of Channel Morphology on Water Quality.

   a. The ability of a stream to transport sediment appears to be directly related to its Unit Stream Power (USP)--the rate of energy expenditure by a stream as it flows from a higher to a lower point. Mathematically USP is a function of water velocity and surface slope of the water.

   b. Unit stream power is useful in predicting sediment loads only when available material equals or exceeds the amount that can be carried in a channel.

   c. A stream naturally decreases its USP and sediment transporting capability by making lateral (meandering) and vertical (pools and riffles) adjustments.

   d. USP is reduced by pools and riffles only at low and intermediate flows. The effect of meanders on USP in conjunction with pools and riffles at various flow rates does not appear to have been quantified.

   e. Channelization destroys nearly all characteristics of "natural" stream morphology, i.e. pools and riffles and meanders. As a result, the USP of these streams is increased and their ability to transport sediment and erode stream banks is enhanced.

   f. Allowing streams to maintain their natural morphology or reinitiate meandering may be a feasible management alternative for improving water quality, especially during periods of low and intermediate flows.

4. Effect of Nearstream Vegetation on Water Temperature and Water Quality.

   a. Removal of vegetation from along headwater streams in agricultural watersheds can result in water temperature increases of 6-9°C.

   b. As water temperature increases, its capacity to hold oxygen decreases, which exaggerates the impact of each additional unit of organic waste added to the system.

   c. Laboratory studies have demonstrated an exponential increase in the rate at which nutrients attached to sediment are converted to readily available forms as temperature increases. Slight increases in temperature above 15°C produced substantial increases in the amount of phosphorus released.

d. Removal of nearstream vegetation along streams in agricultural watersheds results in blooms of nuisance algae and periphyton due to elevated temperatures, rate of nutrient release from sediment, and light availability.

e. An examination of temperatures in various streams with different types of vegetation indicates that angular canopy density (a measure of the shading capability of the vegetation) is the only characteristic of the vegetation correlated with temperature control. Width of the vegetation strip is not important.

f. Small streams in agricultural watersheds have the greatest temperature problem but they are also the easiest to control with nearstream vegetation, due to the inverse relationship between temperature change and stream discharge for a given input of thermal radiation.

5. Effect of Nearstream Vegetation and Stream Morphology on Stream Biota.

a. Sediments reduce the structural complexity and productivity of aquatic plant, invertebrate and vertebrate communities. Their detrimental effect results when they settle out of suspension, cover the periphyton and essential spawning grounds of fish and decrease bottom (substrate) diversity.

b. When vegetation is removed along streambanks and water temperature increases from 6-9°C, it may become energetically impossible for species with lower temperature optimums to continue living in an area, regardless of changes in sediment load, habitat structure or other environmental conditions. A shift in community structure may occur with resident species being replaced by less desirable species which are more tolerant of the increased temperatures.

c. Headwater streams (stream orders 1, 2, and 3) are dependent on nearstream vegetation as a major source of energy and are extremely important as spawning and nursery grounds for many commercial and sport species which spend their adult lives in rivers or large lakes. Removal of nearstream vegetation in these areas results in significant reductions in invertebrate and fish production because of the loss of allochthonous (terrestrial) energy inputs.

d. Channelization results in a significant reduction in invertebrate and vertebrate production due to the destruction of habitat complexity. Recent research relating stream morphometry to habitat characteristics of aquatic organisms indicates that maintaining stream sinuosity and a diversity of depths, water velocities, and substrate types will lead to substantial improvements in the quality of stream biota in agricultural watersheds.

e. Because organisms are simultaneously adapted to a number of different environmental gradients, any attempt to improve the quality of the stream biota must utilize a broad-based, multi-purpose approach. Future stream management practices must optimize for a number of environmental variables, including flow characteristics, water temperature, oxygen concentration, habitat diversity, food availability and water quality, all of which interact to determine the quality of the stream biota. Data in the literature suggest a more realistic management of nearstream vegetation and stream morphology can provide the basis for such an interactive approach and lead to a more productive, diverse, and stable biotic community.

6. Feasibility of Greenbelts.

   a. The conclusions listed above suggest that proper management of nearstream vegetation and stream morphology may produce substantial improvements in water quality and the stream biota of agricultural watersheds. Vegetation may reduce sediment and attached nutrient inputs to streams and temperature fluctuations. A more natural stream morphology can reduce sediment loads and provide suitable habitat for both fish and invertebrates.

   Therefore, before major improvements in water quality and stream biota can be realized, the present emphasis on erosion control on the land surface must be combined with the management of nearstream vegetation and stream morphology. This approach will require a substantial new research effort on a number of questions outlined in the recommendations section of this report. These problems must be dealt with at individual drainage and watershed levels before the environmental and economic feasibility of this management strategy can be fully evaluated.

SECTION 3

RECOMMENDATIONS

We have divided our recommendations for future studies into two broad categories: (1) research aimed at providing answers to specific questions dealing with the possible use of nearstream vegetation and/or stream morphology for improving water quality and the stream biota and (2) large-scale research projects to be initiated at the single drainage or watershed level to clarify the economic costs and benefits of the greenbelt management alternative. We also briefly comment on the benefits and costs of these two research approaches with respect to solving water quality problems in the non-point source area.

SPECIFIC RESEARCH PROBLEMS

1. Vegetation as a Nutrient Filter

    a. Substantially more research needs to be done elucidating variables important in determining the levels of nutrients in subsurface flows. Emphasis should be placed on the effects of soil type, slope, drainage characteristics, and type and quality of tile line.

    b. Four factors should be more rigidly controlled in attempts to determine the efficiency of vegetation for filtering nutrients from surface runoff:
        (1) Detention time: should be accurately quantified so that filtering success can be more precisely related to this variable.

        (2) Vegetation effects: controls should be maintained to clarify the relationship between type of vegetation and nutrient removal with specific emphasis on the effects of (a) structure and physiological capabilities of the plants and (b) single plant species versus more complex plant communities.

        (3) Volume of water treated: the relationship of volume of water treated to efficiency of nutrient removal should be studied in more detail.

        (4) Soil type: soil type affects filter efficiency, with sandy loam soils being more efficient than clay loam soils. More attention should be directed to this variable, especially with respect to its effect on shallow percolation into the soil versus rapid overland flow of the solution.

2. Vegetation as a Sediment Filter

Before nearstream vegetation can be efficiently utilized as a land management alternative for improving water quality, the following problems must be addressed:

a. The importance of runoff over streambanks as a sediment source versus runoff entering streams from intermittent tributaries and waterways needs to be established. How does the contribution from the two sources change with stream size (stream order)?

b. The relationship between efficiency of sediment filtration and volume of runoff, initial sediment concentration, size distribution of the incoming sediment, filtration length, slope of the filter, characteristics of the vegetation, and degree of filter submergence should be established for runoff conditions encountered in typical agricultural watersheds.

c. The quantitative relationship between the retardance of flow, vegetation type, and filtering efficiency should be established and its implications for an economic cost and benefit model be evaluated.

d. For different vegetation types the shape of the curve relating distance the water has passed through the filter to percent of sediment remaining should be established and an evaluation of why vegetation types differ should be performed.

e. The duration of effectiveness of vegetative filters should be established along with how arrangement of the strip(s) of vegetation affect its efficiency and/or duration of effectiveness.

f. Harvestable crops should be evaluated to determine their value as a vegetative filter and their potential as an economic incentive for filter use.

g. The effect of surface litter on filter efficiency and the longevity of effectiveness of the filter should be evaluated.

h. The effect tillage practices have on filter efficiency by reducing peak rates of runoff should be established.

i. The effect of filters along streambanks in reducing erosion from flood waters should be examined along with their effect on sediment deposition by flood waters.

j. The effect of nearstream vegetation on drainage rates in agricultural watersheds should be systematically established and evaluated with respect to the economic costs and benefits of this decreased drainage rate.

k. The amount of land to be taken out of production to minimize nutrient and sediment loads must be determined.

3. Effect of Channel Morphology on Water Quality

   a. The relationship between stream morphology, Unit Stream Power (USP), and suspended sediment concentration should be rigorously evaluated in agricultural watersheds to establish the effect of present stream management practices on USP, suspended sediment load and total sediment load leaving a watershed.

   b. A systematic evaluation of the effect of stream morphology on drainage rates in headwater streams should be performed to establish what options are available, depending on the balance desired between the goals of agriculture (rapid drainage) and those of water quality (slower drainage, lower USP's, reduced suspended sediment loads, and reduced downstream flood and silt damage).

4. Predicting Sediment Loads in Flowing Waters

   a. A realistic model for predicting sediment losses from agricultural watersheds is critically needed. Among other things, the model must consider the magnitude of erosion from the watershed, how and where eroded material is removed before the runoff reaches waterways, the addition of sediment from underground (drain) tile systems and the energy the stream has available to transport the sediment entering it. Future research should emphasize combining the Universal Soil Loss Equation, information concerning the nature of the erosion-deposition equilibrium between the terrestrial and aquatic environment, and the Unit Stream Power model.

5. Stream Biota

   a. Systematic experiments should be performed on headwater streams, evaluating the effect of removal of nearstream vegetation on the distribution and abundance of organisms in these areas.

   b. A multivariate analysis should be performed relating invertebrate and vertebrate abundance and diversity to several relevant environmental variables. This would provide significant insights into what combination of water quality and stream morphometric variables are of prime importance in determining the quality and quantity of stream biota. This data could then be utilized to make significant improvements in future engineering designs for alteration of the nearstream vegetation and channel morphology.

   c. A rigorous economic re-evaluation of all aspects of channelization should be performed.

6. Floodplain Ecology

   Ecosystems which have evolved in the regular flooding regimes of small stream or river floodplains require periodic flooding for normal growth and reproduction. Modifications of stream channels by channelization and by construction of dams modifies the periodicities of flood and result in shifts in species composition of floodplain floras. Such problems may preclude management for natural vegetation along streams and the benefits deriving from their presence. Any efforts to assess the value of greenbelts should consider both "artificial" and "natural" assemblages of species. Intuitively, it seems likely that more natural assemblages will optimize a wider range of societal objectives.

LARGE SCALE RESEARCH

Before the use of nearstream vegetation and channel morphology can be fully evaluated as a management alternative, its costs and benefits must be assessed at the level of a single drainage and at the watershed level. The design of this research must explicitly recognize the functional interrelationships of the terrestrial and aquatic components of watersheds. For example, research examining the effects of tillage practices alone compared with other research on the effects of greenbelts and/or more natural channel morphology is inadequate. Significant benefits may derive from combinations of several practices that do not accrue from either practice used alone.

1. Changes in nearstream vegetation could be instituted in a watershed by preventing plowing along one or several of the drainages and letting vegetation recolonize the area or by planting some selected species. The effects of nearstream vegetation on water quality, rate of stream discharge, and total sediment discharge could be evaluated. Unless this type of land treatment could be performed on a number of different drainages with different stream morphologies, substantial insights into the interaction between nearstream vegetation and stream morphology will not be forthcoming. However, it could provide a sound data base for the economic evaluation of the costs and water quality benefits from alternate management strategies of the nearstream vegetation.

2. To evaluate the combined effect of nearstream vegetation and channel morphology on water quality and quality of the stream biota, a number of streams differing in distance to nearest cropland and in the length of time since removal of nearstream vegetation and channelization should be intensively studied. Depending on the length of time since alteration, the streams would differ in type of vegetation along their streambanks and the degree to which new meanders and pool-riffle sequences have developed. An intensive examination of water quality, sediment transport, and the structure of biotic communities in these streams would provide a substantial data base and significant insights into how the terrestrial-aquatic interface and stream morphology can be more efficiently managed to maximize the quality of the water and biota in agricultural watersheds and minimize the costs.

WHAT TYPE OF RESEARCH IS BEST?

In this section we have outlined a number of both specific and broad research problems which could be undertaken to more fully evaluate the feasibility of the greenbelt management alternative. Although it would be best to extensively investigate each of these problems, time and resource limitations demand that those problems with the highest benefit-cost ratio be investigated first. As we have documented in this report, the quality of water leaving a watershed and the quality of the stream biota are based upon complex interactions on the land surface, in the stream, and between the land and stream. The classical reductionist approach of controlling as many variables as possible and examining the effect of one or a series of treatments will be difficult (if not impossible) and expensive to do at the watershed level and will probably have limited success in identifying feasible, *comprehensive* management strategies for controlling non-point pollution; the interactions between the variables are too important and the variables are too numerous. Rather, we emphasize the need for a more holistic approach towards the solution of non-point pollution problems in which emphasis is placed on identifying groups of interacting variables which, if properly managed, can lead to significant improvements in a broad range of water quality problems. We believe the nearstream vegetation and stream morphology are two such variables. Future research should document the magnitude of the benefits and costs produced through the interaction of these variables along with their feasibility of implementation.

SECTION 4

VEGETATION AS A NUTRIENT FILTER

Previous studies investigating the use of vegetation to remove nutrients from solution are largely associated with the renovation of secondary effluent by spray irrigation techniques. These methods rely on rapid infiltration of the solution with both the vegetation and soil acting as a filter medium. Nutrients are removed through uptake by plant roots and microorganisms and by chemical adsorption of the ions onto the surface of soil particles. Studies of the use of combined soil and vegetative filters suggests considerable effectiveness at phosphorus removal (98-99%), with lower efficiencies for removal of nitrogen (10-60%) and other nutrients (Lehman and Wilson 1971, Kardos et al. 1974, Sopper and Kardos 1973, Younge et al. 1976, Inst. Water Research, Michigan State University 1976). The effectiveness of vegetative-soil filters appears to be related to soil and vegetation type and quantity of effluent applied to the system. Unfortunately, long term effects on soil nutrient loads are still not clear.

We will not consider "infiltration filters" in further detail in this report, since we are primarily interested in the feasability of using vegetation to remove nutrients from shallow overland flow and not percolation of solution into the soil. (We were not able to find experimental studies on the use of vegetation to remove nutrients from channel flow.) An excellent example of the use of grass filters to remove nutrients from overland flow was conducted by the Campbell Soup Company in Paris, Texas (Mather 1969, Law et al. 1970). Wastewater was sprayed on the top of grass plots 60 to 90 m long with a slope of one to 12 percent. Because of the impermeability of the soil, an average of 61% of the water applied left the area as surface runoff. Chemical analyses of the runoff showed that BOD and nitrogen removal varied from 85-99% and 76-90%, respectively. However, the efficiency of phosphorus removal was dependent on application frequency, with the percent removed increasing from 50 to 80% by a change in the spray schedule from once a day to three times a week. Detention time was a key factor controlling both nutrient and BOD removal but quantitative information relating detention time to percent reduction was not given.

Other studies using grass filters to remove nutrients from municipal effluents were not as successful. In one study, effluent from an oxidation pond was applied to grass plots 300 m long (Wilson and Lehman 1966 in Butler et al. 1974). Apparently only one trial was performed and nitrogen and phosphorus concentrations were reduced 4 and 6%, respectively. Information regarding application rate and slope were not available and detention times were not given.

A similar study (Butler et al. 1974) applied secondary effluent to reed canarygrass plots 150 feet long with a 6% slope. Reductions in phosphate and nitrate concentrations were only 0-20%. Insufficient contact time, due to high flow rates and a short flow distance, was suggested as the reason for the inefficiency of the system.

Popkin (1973) performed a series of tests using a grass covered soil filter for renovating urban runoff in Tucson. The filter was 60 m long, 1.2 m wide and 1.5 m deep. The volume of water treated per acre of grass per day varied from 3.8 to 25.1 acre feet. For the grass filter, the following percent reductions compared to untreated runoff occurred: COD-62%, suspended solids-35%, turbidity-97%, total coliforms-84%, and fecal coliforms-87%. The efficiency of the filter for removing nutrients was not reported.

The treatment of feedlot wastes by grass filters is a rapidly expanding area. The systems used usually consist of a lagoon for settling of solid wastes followed by a grass waterway through which the lagoon effluent is allowed to filter. Much of the research in this area has just been initiated and extensive sets of data are not yet available (D. H. Vanderholm, Associate Professor of Agricultural Engineering, University of Illinois, personal communication, 1976). The grass waterways used are usually long, i.e. 260-800 meters (Sievers et al. 1975, Swanson et al. 1975) but even extremely long waterways, up to 3600 meters, have not been successful at reducing nutrient concentrations (Kreis et al. 1972). Furthermore, when systems are successful (Edwards et al. 1971, Swanson et al. 1975) it is difficult to determine if the reduction in nutrients is due to some action of the vegetation or is merely a result of dilution by water entering the waterway from the cropland area.

From this brief literature review it is clear that the use of vegetation for removing nutrients in solution from surface runoff is not always successful. The reasons for success, or lack of success are not always clear. We suggest four factors should be more rigidly controlled and evaluated in future research:

1. Detention time: it should be accurately quantified so that filtering success can be related to detention time and slope of the filter.

2. Vegetation effects: when possible, controls should be maintained to more fully elucidate the relationship between type of vegetation and nutrient removal with special emphasis on the effects of (a) structure and physiological capabilities of the plants and (b) single plant species versus more complex plant communities.

3. Volume of water treated: the relationship of volume of water treated to efficiency of nutrient removal should be studied in more detail.

4. Soil type: soil type affects filter efficiency, with sandy loam soils being more efficient than clay loam soils (Mather, 1969). More attention should be directed to this variable, especially with respect to its effect on shallow percolation into the soil versus rapid overland flow of the solution.

Even if these variables are properly evaluated, certain problems must be clarified before final recommendations for use of vegetation to control nutrient inputs from agricultural runoff can be made. First, a common assumption is that nutrients like phosphorus are entering streams via surface runoff rather than subsurface or groundwater runoff. This is probably true under most circumstances. Some studies (Jones et al. 1975, Hanway and Laflen 1974) have found very small quantities of phosphorus in tile flows and they have been much less than concentrations in surface flows. However, when tile lines have surface intakes, including along road ditches, they may carry significant amounts of nutrients and sediments (R. Bachman, Iowa State University, pers. comm.).

Other recent reports (Ryden et al. 1973, Sommers et al. 1975a,b) also suggest substantial inputs of phosphorus from subsurface flows. In some cases concentrations of N and P were comparable to or greater than those in surface runoff in the Black Creek watershed (Sommers et al. 1975a). Based on average concentrations, tile effluents and surface runoff were equally important sources of nutrients entering surface waters. Variability in the importance of subsurface inputs among watersheds is due to differences in soil, slope, drainage characteristics, and quality of tile lines. Observations at Black Creek suggest that very efficient surface filters, if acting alone, may have limited potential for controlling eutrophication when inefficient tile systems are present. This is especially true in streams where small concentrations of nutrients from subsurface flows could have substantial effects when moderate flow velocities are involved (Phaup and Gannon 1961). The conflicting results outlined above suggest the need for more research on the variables important in determining the levels of nutrients in subsurface flows.

Second, the distribution of nutrients between the solid and aqueous phases of runoff must be examined. Again data from Black Creek are relavant to this question. Sommers et al. (1975a) and Nelson et al. (1976) found that a large proportion of nitrogen and phosphorus in surface runoff is attached to sediment (Table 1). With fertilizer additions, a slightly larger proportion of the nutrients are in the solution phase of the runoff but even then nearly all of the phosphorus (greater than 85%) and most of the nitrogen (greater than 70%) is attached to sediment. (Although nutrients adsorbed to sediment particles are not directly available to plants, removal of nutrients in solution by plants will result in movement of some of the adsorbed nutrients from sediment particles to solution. In solution they are directly available to biological systems.)

Soil types differed only slightly, with clay loams typically having a smaller fraction of the nutrients in solution. Nutrients are usually adsorbed to the smaller sized particles, especially clay (Sommers et al.

1975a,b, Scarseth and Chandler, 1938, Monke et al. 1975b) and this is also the soil fraction that is selectively lost during the erosion process (Stotlenberg and White 1935, J. V. Mannering, personal communication, Professor of Agronomy, Purdue University, 1976).

TABLE 1. PERCENT OF NITROGEN (N) AND PHOSPHORUS (P) ATTACHED TO SEDIMENT IN SURFACE RUNOFF FROM FOUR SOIL TYPES UNDER FERTILIZED AND UNFERTILIZED CONDITIONS (Adapted from Sommers et al. 1975a)

Soil Treatment	% N as Sediment N		% P as Sediment P	
	Average	Range	Average	Range
Fertilized	75	49-91	92	85-98
Unfertilized	88	69-98	96	91-100

These observations suggest four main conclusions regarding the use of vegetation as a nutrient filter:

1. There has been variable success in the use of vegetation to filter nutrients in solution from surface runoff. The reasons for this variability are largely unknown due to poorly controlled experiments.

2. Even at high efficiencies of nutrient removal, in some agricultural areas surface filters acting alone may not control eutrophication because of the inputs of nutrients into streams via subsurface pathways. This does not imply that surface filters should not be used. Rather, we emphasize that no single factor is likely to solve the problem.

3. Conflicting data exists regarding the importance of subsurface inputs of phosphorus into streams. More research is needed to clarify the effects of soil type, slope, drainage characteristics and type and quality of tile lines on this variable.

4. Substantial amounts of nutrients can be removed from surface runoff by removing sediments, especially the clay fraction, to which the nutrients are attached.

SECTION 5

VEGETATION AS A SEDIMENT FILTER

Three potential sources of sediments exist: (1) streambank erosion, (2) subsurface inputs (i.e. tile), and (3) surface inputs. The value of vegetation as a sediment filter depends on the relative amounts of sediment from these three sources. Data from Black Creek suggest that streambank erosion is a minor source of sediment inputs (Wheaton 1975, Mildner, 1976) especially if treatment is applied to the few sites where most bank erosion occurs. Studies of surface versus subsurface inputs at Black Creek yielded conflicting results. Some tile effluents contained low sediment concentrations while concentrations in others were large enough to suggest tiles may contribute a significant amount to the sediment yield from watersheds (Monke et al. 1975a). There are probably two reasons for the variability of the data obtained. The samples were random "grab samples." As a result they varied depending on when they were taken relative to the last storm event. Furthermore, the concentration of sediment in tile outflows is significantly influenced by the quality of the tile line (Karr, personal observ.). This latter point, along with more recent data from Black Creek indicating that surface runoff accounts for 50% of the water and 99% of the suspended solids loss in the watershed (Nelson et al. 1976), suggests maintenance of tile lines will insure that surface runoff will be the main source of sediment inputs into agricultural drainages. Sediment inputs into streams can therefore be controlled by adequate treatment of surface runoff.

Wischmeier (1962) examined the effect of storm intensity on erosion and demonstrated that about three-fourths of the total soil loss from agricultural land occurs during an average of four storms each year. A more recent study suggests caution in such conclusions (Piest 1963). He found that the sediment contributions of large storms (with a return period greater than 2 yrs.) varied from 3-45% of total suspended-sediment yield; the yield from moderate storms (1-2 yr. return period) ranged from 3-22% of total yields and storms with a return period of less than 1 yr. carried 34-92% of total suspended sediments. Since small storms carried more than one-half of the soil losses in most watersheds, small scale conservation practices with low cost can result in significant reductions in downstream sedimentation (Piest 1963). Piest also concluded that the soil losses resulting from large storms were higher in the semi-arid Great Plains than in the humid Southeast. Furthermore, relative sediment contributions for a given large storm decrease with increasing watershed size.

Therefore, in most watersheds, filters can contribute significantly to the reduction of sediments if they are efficient during low storm intensities. If they can also be demonstrated to be efficient at high storm intensities an even greater contribution to the reduction of sediments will result.

This section of the report examines (1) the ability of vegetation to filter sediment from water which spreads as a shallow layer more or less uniformly over the surface of the land (overland or sheet flow) and (2) the ability of vegetation to filter sediment from shallow channel flow entering streams as intermittently flowing tributaries or waterways (channelized flow).

OVERLAND FLOW

Unfortunately only a minimal amount of data has been found regarding this topic. Much of the work in this area is descriptive, relating to the effectiveness of filter strips between logging roads and mountain streams. In Idaho, Haupt and Kidd (1965) observed that sediment flows off logging roads during major storm events reached streams if the undisturbed filter strip was only 2.5 m wide but did not if they were 9 m wide. In Montana, silt flows off skid and logging roads fanned out and deposited sediment soon (6-9 m) after reaching an undisturbed mat of pine needles and other forest litter (Johnson 1953).

The relationship between the slope of a vegetative filter and minimum effective greenbelt width for treatment of surface runoff is direct (Fig.1; Trimble and Sartz 1957). Generally minimum width of filter strips increases with slope of land and varies with water quality objectives. Where maintenance of the highest possible water quality is important, such as in municipal watersheds, recommended filter widths are higher (Trimble and Sartz 1957). However, the scatter of their original data suggests that other variables are also determining the efficiency of the filter. Apparently, increased flow velocity results from increased slope and enhances the ability of the surface flow to transport sediment. Although some recommendations for greenbelt width are in the literature, little or no data are given. Recommendations, then, must be viewed as tentative. Significantly, in filters observed for long periods of time (i.e., 15 months), sediments did not clog the loose surface litter nor decrease the efficiency of the filter. Trimble and Sartz suggested that leaves fall each year and form a fresh surface for deposition of new sediment. This indicates that sediment filters may be effective for long periods of time without sediment buildup along streambanks due to natural variability in the plant community from year to year (Gosz et al. 1972). However, the length of the effective period must be examined by more detailed, long-term research.

More elaborate equations were later developed for predicting the sediment flow distances using multiple regression techniques (Haupt 1959, cited in Broderson 1973). Sediment flow distance is primarily a function of (1) slope of the filter and the density of obstructions within the filter, i.e. grass, brush, tree stumps, depressions, etc. and (2) the slope and length of the embankment which the runoff passes down before it enters the filter. More recently, Ohlander (1976) developed an equation to predict the size of buffer required to trap sediment exitting a logging road drainage. His prediction was based on soil erodibility (K--see page 40), slope of the filter, and the infiltration rate of water into the filter.

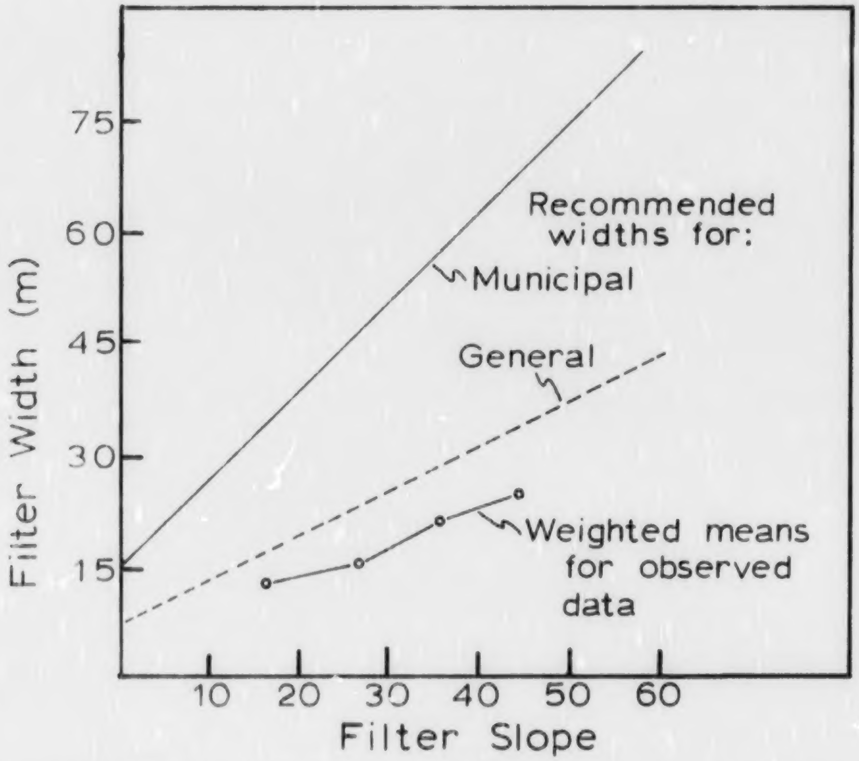

Figure 1. Relationship between slope of a vegetative (sediment) filter and effective filter width. Note that the recommended widths are "evaluated guesses" rather than empirically defined widths. As noted in the text the scatter of data is broad suggesting that a number of factors may be important in determining optimal filter width. (Modified from Trimble and Sartz 1957).

Although much work evaluating the use of natural vegetation for filtering sediments from overland flow has been conducted by foresters, relatively little has been done in agricultural watersheds. One study relevant to this problem (Mannering and Johnson 1974) passed sediment-laden water through a 15 m strip of bluegrass sod (Table 2). They found in a single trial that 54% of the sediment was removed from the water.

Studies of surface runoff through heavy cornstalk residue on the lower 3 m of a 11 m erosion plot carried only 3-5% of the sediment expected from a bare surface (G. R. Foster, pers. comm.). The study was done with simulated rainfall (6.2 cm per hour). Foster, an hydraulic engineer with USDA-ARS in West Lafayette, Indiana, felt that well-designed and maintained grass strips would be more effective at sediment removal than is reflected in the P values of the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1965).

TABLE 2. EFFECT OF A BLUEGRASS SOD STRIP ON SEDIMENT CONCENTRATION IN RUNOFF (Modified from Mannering and Johnson 1974)

Distance into sod strip (M)	Slope between sample points (%)	Sediment concentration expressed as percent of original
0	4	100
3	20	78
8	4	66
15		46

The effect of grass and presumably other vegetation types on sediment load is really a two-fold phenomenon. The studies already mentioned document the value of vegetation or surface litter for reducing the amount of sediment in a given volume of water. A second benefit is the reduction in volume of runoff from vegetated areas.* USDA studies on demonstration plots in Wisconsin (0.04 hectares-400 sq. meters) have shown that runoff from grass is one-fifth of that from continuous row crop plots (Glymph and Holtan 1969). Rotations with grain or hay had intermediate delivery rates. They concluded that runoff is inversely related to the density of vegetation and frequency of cultivation. When forested watersheds are compared to areas under intense cultivation,differences in runoff may be as great as 40X (Hornbeck et al. 1970). Hewlett and Nutter (1970) have shown that in natural watersheds overland flow is a rare phenomenon. The retardance of the flow by the vegetation allows the soil to absorb much of the water, which then goes on yielding it to the stream for extended periods of time (Fig. 2). The results of this are (1) the water is passed through a soil filter before entering the stream and (2) there is a more controlled release of water from the watershed, resulting in a more stable water supply and aquatic environment (Curry 1975). On land with reduced vegetation cover, the probability of flooding increases and seasonal shortages of water are more common. This suggests that incorporation of greenbelts along streams might not only reduce sediment loads but also produce small reductions in runoff. Vegetation, with associated litter and soil characteristics, might serve as a sponge to hold water for a slow release amd more stable aquatic environment. Incidentally, the same objectives (slow release and reduced sediment loads) may be accomplished with some construction practices such as parallel tile outlet terraces.

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*Actually a third factor is also important. Rainfall impact on soil structure is reduced when it strikes vegetation before reaching the soil surface. These factors are dealt with implicitly in the C and P terms of the USLE. A clearer definition of their relative importance is required.

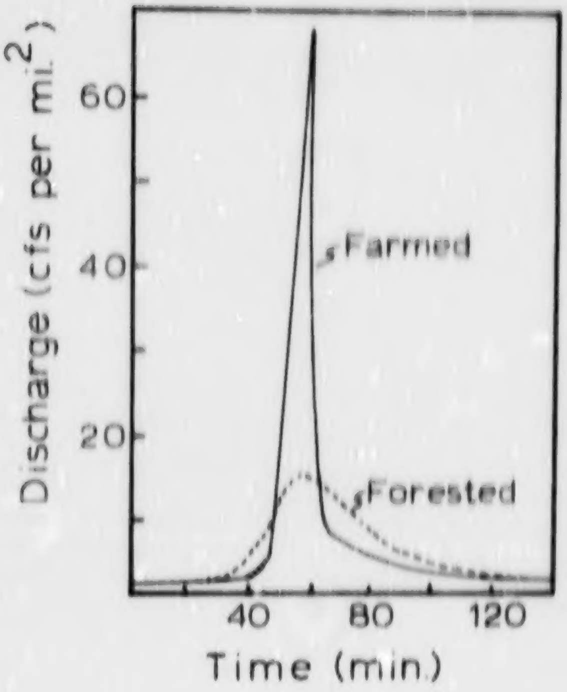

Figure 2. Effect of land use on discharge rates on two watersheds (Modified from Borman et al. 1969).

In summary, limited data indicates that vegetation and surface litter can effectively remove sediment, and perhaps reduce runoff, from surface flow before water reaches channels. However, the size and type of vegetative strip needed to remove a given fraction of the overland sediment load or its effect on rate of water release cannot be established at this time.

CHANNEL FLOW

Early observations documenting the ability of vegetation to act as a sediment filter in channels are primarily descriptive. When tamarisk invaded an area along a stream above a reservoir in Carlsbad, New Mexico, the stream spread across a broader flood plain, decreased its velocity, and deposited sediment around the tamarisk (Tamarix gallica) rather than in the reservoir (Brown 1943). This resulted in a decrease in the rate of silt deposition in the reservoir (Fig. 3). Similar observations were made by others (Taylor 1930) but quantitative measurements of the effect of vegetation on flow velocity and efficiency of sediment removal were not performed.

Other more quantitative field experiments examined the effect of vegetation on the flow of water in open channels (Cook and Campbell 1939, Palmer

1946, Ree and Palmer 1949, Ree 1949). Although designed to evaluate scouring problems, they provide quantitative documentation of how vegetation affects the velocity of water.

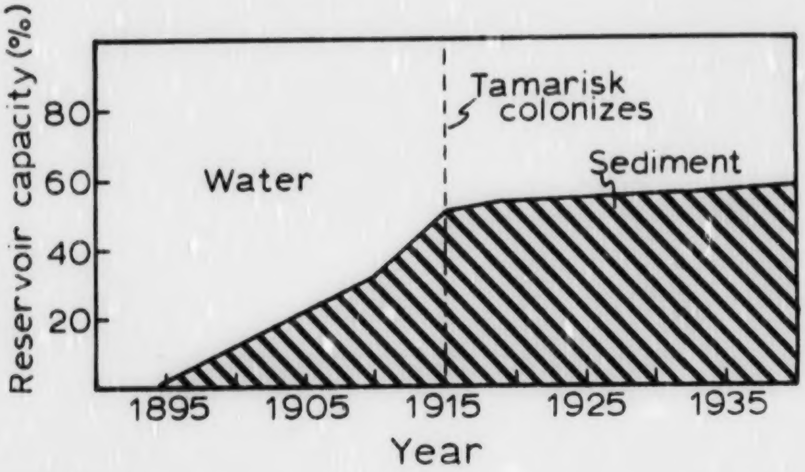

Figure 3. Silt volume as percent of basin capacity for Lake McMillan near Carlsbad, New Mexico. Flattening of the curve after 1915 is attributed to the effect of tamarisk in the valley above the head of the reservoir (Modified from Brown 1943)

When water depth is less than the grass height, velocities tend to be low (Fig. 4). From the channel bottom to the top of the grass the velocities do not exceed two feet per second. At the upper surface of the vegetation the velocity increases rapidly. These results suggest (1) a substantial reduction in the flow velocity due to the retarding action of the vegetation, (2) deposition of a fraction of the sediment the runoff is carrying, (3) the effectiveness of the vegetation at retarding the runoff and allowing deposition of sediments depends on the relationship between the depth of runoff and the height of the vegetation and (4) reduced water velocities retard drainage. When water velocities are slowed enough to retard drainage the potential for crop damage exists. Vegetative filters should be designed so that water is not detained long enough to damage corn or soybeans, i.e. 4-6 days (Hamilton 1969), but sufficiently long to provide a more regulated release of water from the land surface and allow sediment deposition to occur. This may also be significant at reducing downstream flooding and erosion due to flooding outside the streambank. This latter point has recently been documented below the washed-out Teton Dam where isolated tree stands prevented excess erosion (N.G. Benson, National Stream Alteration Team, pers. comm., 1976).

The importance of depth of runoff is further illustrated in Figure 5. Maximum flow retardance is obtained during low flows since vegetation is still upright (neither bent nor submerged). The gradual increase in retardation in this range is probably due to the greater surface area of vegetation

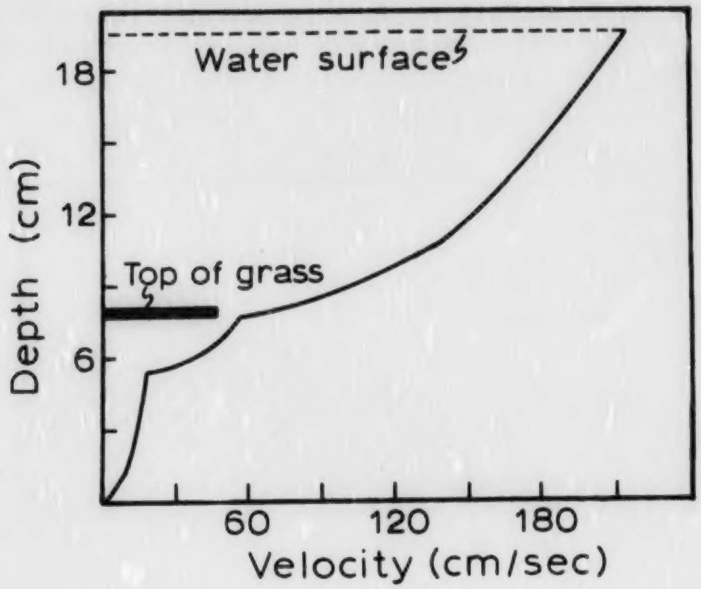

Figure 4. Water velocity as a function of depth. Note that velocity increases rapidly near the top of the grass and even faster for channel flows exceeding grass height (Modified from Ree 1949).

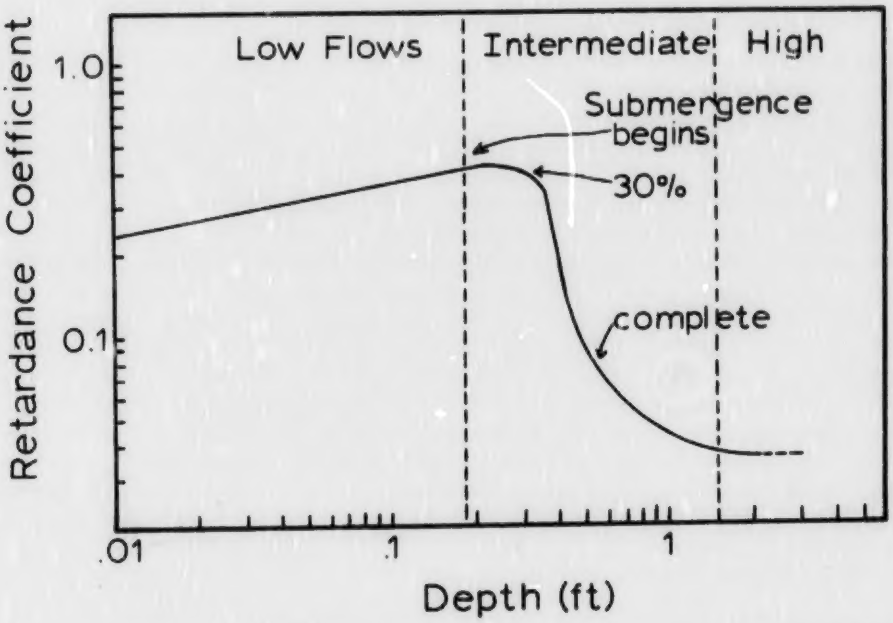

Figure 5. Relationship between depth of flow and amount of retardance with bermudagrass (Modified from Ree 1949).

encountered with increasing depth. As the depth is further increased, the plants start to bend and retardance of the flow is decreased. Finally the vegetation is shingled or flattened and offers little or no resistance to the flow of water. This indicates that flexible vegetation may be inefficient at filtering sediment from channel runoff of large depths, i.e., 0.1 m or larger. The exact depth will of course depend on both the height and flexibility of the vegetation. This effect of depth on filtering efficiency has been partially substantiated by Wilson (1967) and the importance of it will be discussed later in this report. (Note that when water depths are low relative to grass height the channel characteristics are similar to those of overland flow filters discussed above.)

More recently, a mathematical model of the sediment filtering capability of simulated vegetation in shallow channel flows suggested that the importance of depth of flow and the effect of vegetation on flow velocity are only two of several factors determining the efficiency of vegetative filters (Trollner et al. 1973, 1975, 1976; Barfield et al. 1975). Using nails to simulate vegetation and glass beads of varying sizes to simulate sediment, the percent of "sediment" trapped in the channel was correlated with the independent variables: (1) slope of the nails, (2) spacing of the nails, (3) particle size, (4) velocity of flow, (5) filter length, and (6) input sediment concentration. Evaluation of the effect of the independent variables was achieved by "optimizing" a linear regression so that the standard error for predicting the percent of sediment trapped from the independent variables was minimized and the correlation coefficient was maximized. The final model revealed that (1) a large percent of the input sediment in a shallow channel is filtered by the "vegetation" and (2) the most important independent variables determining the fraction of sediment trapped are, in order of importance, flow velocity, depth of flow, spacing of "grass" blades, sediment size, and filter length.

In a similar experiment stiff, medium, and high flexibility strips of plastic proved to be efficient sediment traps (Kayo et al. 1975). At high velocities filter efficiency decreased due to bending of the flexible strips. This suggests that the relationship between depth of flow and retardance illustrated in Figure 5 is also a function of flow velocity.

These simulations and models cannot be used to predict the efficiency of real vegetation as a sediment filter. They are restricted to an artificial set of independent variables thought to be important and are evaluated in a non-random and artificial sequence. As a result they ignore other variables which may be more important in the real world, i.e. the effect of duration of input into the filter, and they fail to evaluate the frequently random and synergistic nature of these independent variables, i.e. a large storm event while the vegetation is still dormant. Therefore their usefulness is limited. Their importance is their clarification of relationships which require more research under natural conditions.

Unfortunately only a minimal amount of data exists to evaluate the efficiency of real vegetative filters in open channels. However, the data are encouraging. Wilson (1967) attempted to develop economical methods for sediment removal from flood waters to allow use of the water for artificial recharge. He allowed turbid flood water to filter through various types of vegetation and analyzed their efficiency at sediment removal. The major findings of his study are discussed and illustrated in the next several pages.

1. Filter efficiency varies with vegetation type. The most efficient species studied to date, coastal and common bermuda grass (Cynodon dactylon), usually removed 99% of the initial sediment concentration (5000 ppm) in 300 m of filtering (Table 3). The percent removed increased with distance. Sediment removal seems to be a decreasing exponential function, differing with vegetation type. This is schematically illustrated by the set of curves in Figure 6. Variation in the efficiency of sediment removal among grasses is correlated with retardance of flow by the vegetation. This finding has two important implications:

    a. Intensive studies are needed to document variation among plants. Limited data already available (Ree 1949, Ree and Palmer 1949) may provide first approximations to suggest which vegetation types should be examined for use as sediment filters.

    b. There will be a trade-off between rapid drainage of the land and amount of sediment removed from the runoff. Clarification of patterns of variation within and between vegetation types must be a major objective of research in this area.

TABLE 3. PERCENT REMOVAL OF SEDIMENT AFTER VARYING LENGTHS OF FILTRATION THROUGH BERMUDA GRASS* (Modified from Wilson 1967)

Grass Species	Distance (M)			
	0	90	215	300
Common Bermuda	0	50.0	90.4	97.0
Coastal Bermuda	0	55.5	97.5	98.5

*Initial concentration - 5000 ppm.

2. Filter efficiency varies not only with vegetation type but also with distribution of particle sizes in the suspended material (Table 4). There is an inverse relationship between the filtration length required to remove a given percent of a particle size and that particle size. This inverse relationship will have two important implications for sizing vegetative filters:

    a. The size distribution of particles in the runoff will have a definite effect on how wide the strips of vegetation must be to filter a given percent of the total load and

b. Emphasis of water quality regulations will have a definite effect on their required width; that is, it may be desirable to remove various volumes of sediment or a given particle size. The preferred alternative will depend on water quality objectives and the local situation.

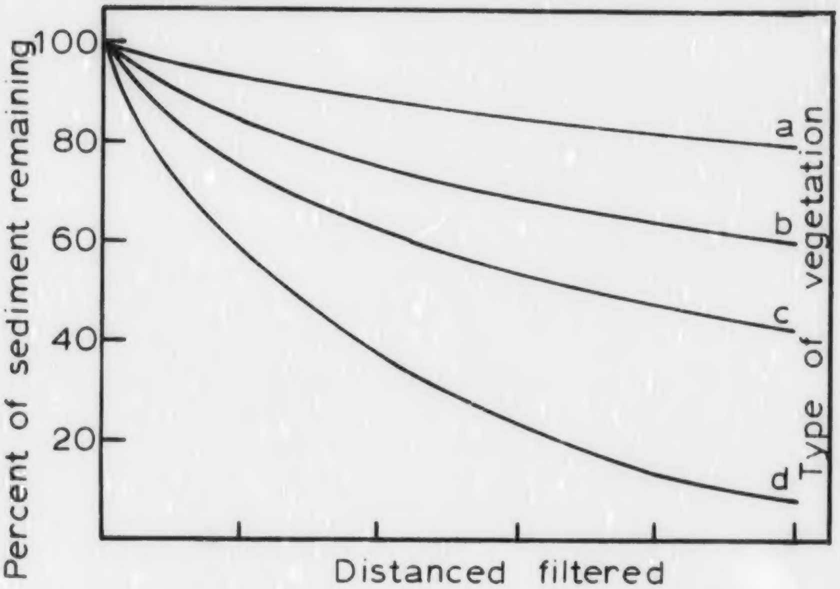

Figure 6. Hypothesized relationship between filter width and percent of sediment remaining for several vegetation types. The four curves are hypothetical. We expect differences among vegetation types but data are not available to show how sediment loads and filter distance will vary among vegetation types.

TABLE 4. PERCENT OF SAND, SILT, AND CLAY IN SEDIMENT DEPOSITED AFTER FILTRATION THROUGH COASTAL BERMUDA GRASS (From Wilson 1967)

Distance from head of filter (M)	Sand	Silt	Clay
3	51.6	40.0	8.4
8	43.2	46.6	10.2
15	3.6	77.0	19.4
30	3.4	69.4	27.2
60	20.2	47.0	32.8
90	31.2	37.6	31.2
120	21.6	39.6	38.8

3. The rate of sediment deposition is constant over a range of slopes. After a critical (threshold) slope is reached, the efficiency of the vegetative filter declines (Table 2). These data indicate the section of the filter with the largest slope (section 2) had the smallest proportion of sediment deposited within it, even though its length was longer than that of section 1 and only slightly shorter than that of section 3. This suggests that not only will vegetation types differ in their relationship between distance runoff is filtered and percent of sediment remaining (Figure 6) but also, for a given type of vegetation, the shape of the curve will differ depending on the slope of the filter. This hypothesized relationship is illustrated by the theoretical curves of Figure 7. More extensive data are needed to substantiate this relationship. The critical slope depends on several factors, including application rate of the water to be filtered, grass characteristics, (surface area, height, etc.) and the particle size distribution of the incoming sediments (Wilson 1967). If the relationship in Figure 7 is supported by field data, the width of the filter required will depend on the slope of the land. Like most environmental technologies this will produce varying effects among farmers depending on the slopes of their land. Under some topographic, soil, or other conditions, filter width may be impossibly large for effective implementation.

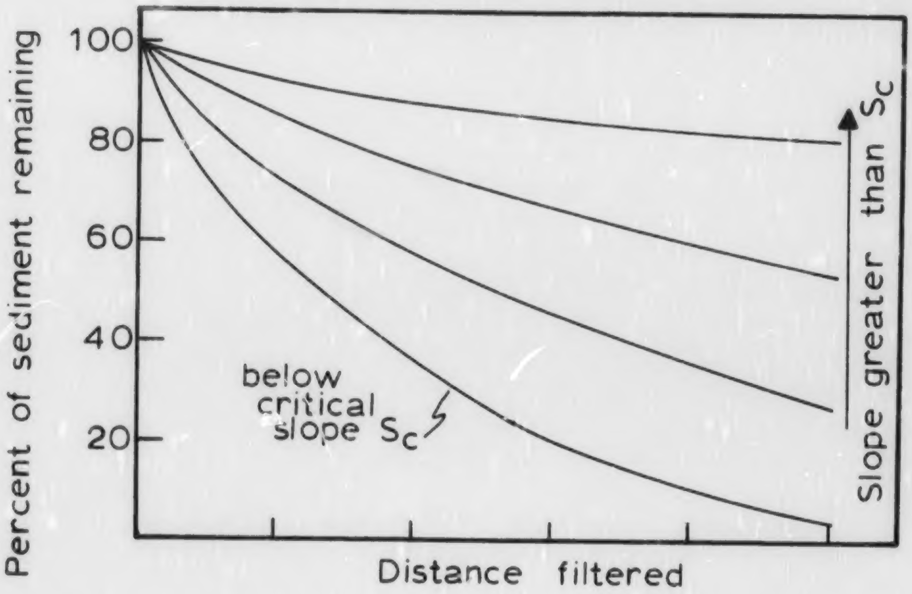

Figure 7. Hypothesized relationship between distance solution is filtered and percent of sediment remaining for several slopes. These are hypothisized curves and assume vegetation type is constant.

4. When grasses are clipped and flow rates are high enough to submerge the grass, filtering efficiency declines to zero. This correlates well with retardance coefficients being lower for shorter grasses than for taller ones and retardance decreasing with increased submergence as shown in Figure 5. It further emphasizes the importance of examining the filter efficiency of vegetation under normal storm runoff conditions. It also suggests that mowing of grass waterways and streamside vegetation should be discouraged, especially during periods when storms are likely.

5. Grasses used for filters should have the following characteristics:

   a. deep root systems to resist scouring in swift currents;

   b. dense, well-branched top growth;

   c. resistance to flooding;

   d. ability to recover growth subsequent to inundation by sediment;

   e. if possible, it should yield an economic return.

It is apparent that several variables are important in determining how effective real vegetation will be at filtering sediments from shallow channel flow. These variables appear to act in an interrelated manner and include filtration length, slope of the filter, grass characteristics, size distribution of the incoming sediments, degree of submergence of the filter, application rate of the water to be filtered and initial concentration of the sediments. Fortunately, many of these same variables were judged to be important by the laboratory studies previously discussed (Trollner et al. 1973, 1975, 1976) and the minimal amount of data regarding filtering from overland flows. Unfortunately there is no quantitative information available on how these variables are interrelated when real vegetation is used as a filter under runoff conditions normally encountered in agricultural watersheds.

An important problem yet to be discussed concerns the placement of these vegetative filters. It is unlikely that a significant amount of surface runoff (and sediment) enters directly into the main channel of a river. Rather it most likely comes in through smaller, often intermittent tributaries, gullies, and drainage ditches which dissect the landscape. Therefore, any use of vegetative filters must concentrate on these areas, especially areas where tributaries enter larger channels. More precise statements on the placement of these filters will require more detailed understanding and quantification of the dynamics of sediment movement at the land-water interface. Only then can a full evaluation of the economic costs and benefits of filters be completed.

The data obtained by this literature review suggests that vegetation can serve as an effective sediment filter. However, the placement of the filter and the width or length of the filter required to remove a given fraction of the incoming sediment, and the duration of its effectiveness is dependent on the interaction of physical factors, biological factors, and the specifications of water quality standards, all of which are yet to be thoroughly evaluated under normal agricultural conditions and quantitatively related to each other in any predictive manner. Present land use practices immediately adjacent to streams (Table 5) indicates these relationships should be investigated. The following questions must be answered before informed nearstream vegetation management programs can be implemented.

TABLE 5 LAND USES IMMEDIATELY ADJACENT TO MODIFIED STREAMS AND DRAINAGE DITCHES IN THE BLACK CREEK WATERSHED (Data from Mildner 1976)

Land Use Type	Modified Stream	Drainage Ditch
Crops	69.9%	74.2%
Pasture	4.7%	0.0%
Forest	17.7%	0.0%
Urban	3.6%	0.0%
Other (Farmsteads, roads, etc.)	4.1%	25.8%

1. How important is runoff over streambanks as a sediment source compared with runoff entering from intermittent tributaries? How do the contributions from these two sources change among land uses and with stream volume?

2. What general relationship exists under normal runoff conditions between efficiency of sediment filtration and volume of runoff, initial concentration of sediment, size distribution of incoming sediment, filtration length, slope of filter, characteristics of the vegetation, and degree of filter submergence?

3. Is there a quantitative relationship between the retardance of flow, vegetation, and filtering efficiency? If so, what are the implications for an economic cost and benefit model?

4. For different vegetation types what is the shape of the curve relating distance the water has passed through the filter to percent of sediment remaining? Why do vegetation types differ in the shape of this curve?

5. What is the duration of effectiveness of the vegetative filter? Does arrangement of the strip(s) of vegetation effect their efficiency and/or duration of effectiveness?

6. Could a sediment filter be harvested and still be effective? If so, this will provide another economic incentive for filters.

7. How much phosphorus can be removed by filtering the sediments?

8. What is the effect of surface litter on filter efficiency and the longevity of effectiveness of the filter?

9. What effect will tillage practices (i.e. contouring vs. straight row) have on filter efficiency by reducing the peak rates of runoff (Glymph and Holtan 1969)?

10. How much will filters along streambanks reduce erosion from floodwaters which overflow stream banks? Will they result in sediment deposition by the floodwaters (Parsons 1963)?

11. How much will greenbelts reduce drainage rates of agricultural land? Will it be economically detrimental?

12. How much land will be taken out of production to minimize sediment and nutrient loads?

We believe the last two questions regarding the economic impact of managing for improved water quality by the use of vegetative filters can only be addressed when more comprehensive information regarding the first ten questions is available.

SECTION 6

EFFECT OF CHANNEL MORPHOLOGY ON WATER QUALITY

Studies of sediment movement and deposition in aquatic environments have largely been from either a geological or hydraulic engineering perspective. Geologists have been primarily interested in sediment deposition (Leopold et al. 1964, Friedkin 1945, Bridge 1975, Jackson 1975) and have directed little attention towards the dynamics of suspended solids. Hydraulic engineers have emphasized the governing processes in the sediment environment, with most emphasis on the shearing flow of fluids, turbulences, and vortices (Chow 1959, Graf 1971).

The relationship between environmental factors like stream morphology and sediment discharge appears to have only recently been examined in any detail in the natural environment (Stall and Yang 1972, Yang 1972). The data found regarding this relationship will be presented here, along with the hydraulic theory relevant to the feasibility of maintaining a more "natural" stream morphology to improve water quality.

There are a number of hydraulic parameters determining the amount of sediment transported within a stream, including intensity of turbulences, velocity of water flow, slope of the water surface, bed roughness, shear stress and many others (Morisawa 1968, Blench 1972). Because these variables are not independent, the precise relationship between them as a group and the sediment load of a stream is difficult if not impossible to establish. As a result, hydraulic engineers have determined the relationship between single variables and sediment transport. Interrelationships between total sediment load and velocity, slope, shear stress or water discharge have been examined (Yang 1972). In many cases predictions of sediment transported by a given flow are possible but conflicting results are also common. For example, for a given water surface slope two different discharges can be observed (Fig. 8) and for nearly identical flow velocities large differences in sediment discharges can occur (Fig. 9). It is apparent that more independent variables and a more process oriented approach needs to be utilized to provide a better predictive capability.

Because of these inconsistencies the concept of unit stream power was proposed to predict total suspended sediment concentrations (Yang 1972, Stall and Yang 1972, Yang and Stall 1974). The concept is an expansion of previous equations and employs two variables, velocity and slope, to predict sediment loads. Basically, they suggest that the rate of sediment transfer is related to unit stream power (USP)--the rate of energy expenditure by a stream as it flows from a higher to a lower point. It is defined as the time rate of potential energy expenditure per unit weight of water in an alluvial channel and can be expressed mathematically in terms of average water velocity (V) and, under steady uniform flow conditions, the surface slope of the water (S) (Yang 1972, Stall and Yang 1972).

$$\text{UNIT STREAM POWER} = \frac{dY}{dt} = \frac{dX}{dt}\frac{dY}{dX} = VS$$

where t = time

Y = elevation above a given datum and is equivalent to the potential energy per unit weight of water
X = longitudinal distance

More complex considerations of lift force, critical velocity, drag force, and particle diameter were added to this basic concept to more precisely estab-

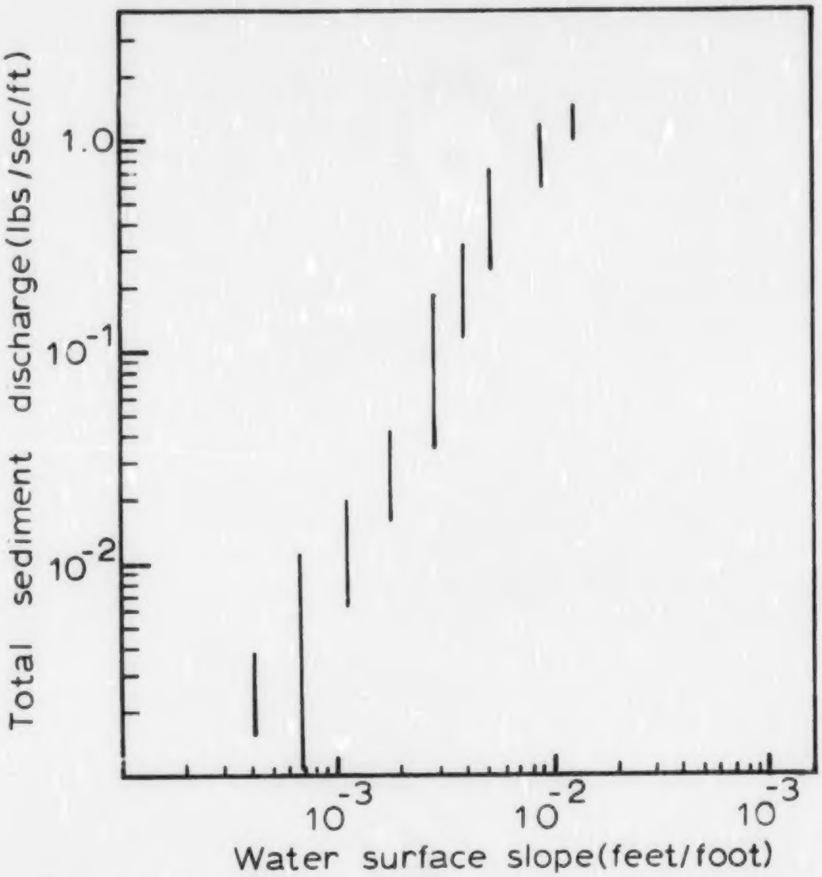

Figure 8. Relationship between water surface slope and total sediment discharge for one set of experimental conditions (Adapted from Yang 1972).

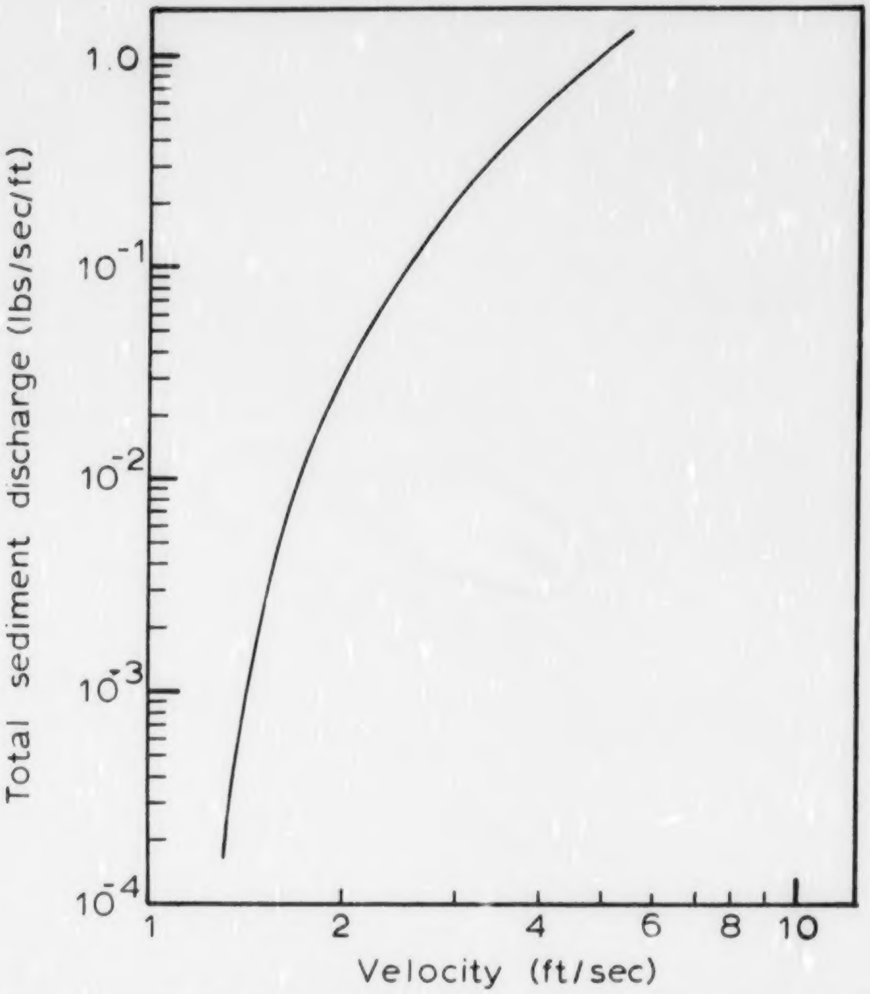

Figure 9. Relationship between velocity and total sediment discharge for one set of experimental conditions (Adapted from Yang 1972).

blish the relationship between USP and sediment transport (Yang 1972, Yang and Stall 1974). For a detailed discussion of these considerations those publications should be examined. The suspended sediment concentration in a stream or agricultural drainage is to a large degree determined by the stream's USP (Fig. 10).

Before we discuss the concept of Unit Stream Power in more detail, it is important to discuss a very important point. The Unit Stream Power concept was developed to predict the amount of energy available to transport sediment. A stream will only carry that amount of sediment which can be transported by the available energy. However, the stream may carry less than that amount if no source of sediment is available. In watersheds with little or no surface erosion and stable banks, sediment loads may be well below the level predicted from consideration of USP. The energy available to transport sediment is only useful in predicting actual sediment loads if other things (sediment availability and other factors discussed below) are held constant.

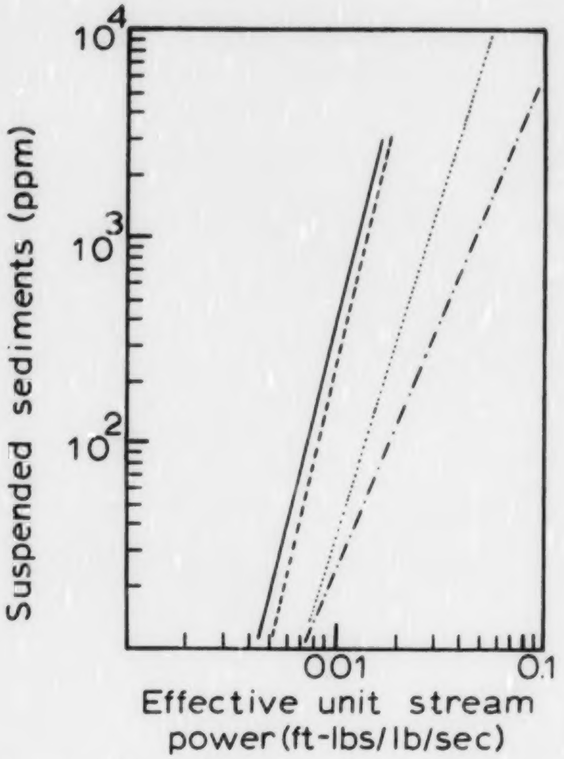

Figure 10. Relationship between effective unit stream power and measured suspended sediment concentration for four streams. (Modified from Yang and Stall 1974).

Although these cautions should always be kept in mind, the concept of unit stream power provides a tremendously useful tool as a first step to understanding a variety of characteristics of stream channels. These include bed roughness, bedform, width adjustments, pool-riffle frequency, meandering characteristics, stream bed profile, and sediment load. (See Blench 1972 for a good, brief introduction into this field.) Basically, a flowing stream has an energy potential which must be dissipated. Man must learn to recognize the extent to which he can minimize the effects of that energy dissipation on water quality and, therefore, on human society.

Two questions will be examined in this section of the report:

1. What characteristics of natural streams or channels control flow velocity, slope, unit stream power, and the potential of the stream to transport sediment?

2. What are the effects of present stream management practices on sediment dynamics in watersheds?

Only the most relevant and "manageable" variables will be discussed here. A more detailed account of other variables which control velocity and slope can be found in Graf (1971) or Chow (1959).

1. Area of Flow: This parameter is critical in determining the velocity of flow for a stream at a given discharge and slope. Its effect is illustrated by the continuity equation from hydraulic engineering:

$$Q = VA$$

where Q = discharge (cfs)

V = velocity (fps)

A = area (ft ^{2})

or from our perspective a more meaningful form

$$\frac{Q}{A} = V$$

Under constant discharge conditions ($Q_1 = Q_2 = Q_n$) differences in velocities (V_1, V_2, V_n) are a function of differences in area of flow. Therefore, for a given discharge under steady and uniform flow conditions, a drainage with a restricted area of flow, such as by confinement in a ditched channel, will have a higher flow velocity than a drainage which spreads its discharge over a larger area. This implies that by channelizing small drainages and concentrating the flow in a minimal area with a maximal velocity, one increases the USP and enhances the capability of the water to erode the stream banks and transport sediment.

2. Roughness Factor (n): The n value for a stream or channel is dependent on factors which affect the roughness of the drainage area, including size and shape of grains on the bed surface, sinuosity of the channel, and obstructions in the channel such as vegetation, logs and sandbars. As roughness increases, n increases and the flow velocity and USP decrease. Values for n have been empirically determined for a number of channel conditions (Chow 1959). Some effects of soil type, channel morphology and vegetation on the magnitude of n are illustrated in Table 6. These data have two important implications:

a. Clean straight channels normally found in agricultural drainages have very low n values. They will have high flow velocities, slopes, and a high capability of carrying large loads of suspended sediment (high USP).

b. Options in stream management practices are extensive in that a broad range of n values, flow velocities, and USP magnitudes can be obtained. For example, preservation of natural stream morphology (meanders, pool and riffle topography) can increase n and decrease flow velocities, slopes, and USP. Therefore numerous options are available depending on the balance desired between the goals of agriculture (rapid drainage) and those of water quality (lower USP's and reduced suspended sediment concentrations).

TABLE 6. ROUGHNESS COEFFICIENTS (n) FOR VARIOUS STREAM CONDITIONS (From Chow 1959)

Description of Stream	Average n
Clean straight channel, full stage, no riffles or pools	0.030
Same as above, but with more stones and weeds	0.035
Clean winding channel, some pools and shoals	0.040
Sluggish reaches, weedy, deep pools	0.070
Natural channel, variation in depth, some logs and dead fallen trees	0.125
Natural meandering river, many roots, trees, brush and other drift on bottom	0.150

It should be emphasized that no data has been found directly relating the effect of altering the roughness of a natural stream on its USP and suspended sediment concentration. From a stream management perspective, further research should be done to more precisely establish the relationship between the two variables.

3. Slope or Gradient of Stream Channel: The main way in which a stream can adjust its slope is via meandering. By doing so, a channel decreases not only its slope but also its USP and potential for transporting sediments (Wertz 1963). Unfortunately, present stream management practices emphasize

maintenance of straight channels which will have larger flow velocities, slopes, USP's and increased potential for transport of sediment and erosion of stream banks (Emerson 1971, Hansen 1971).

The magnitude of the effect of several of these variables on USP was demonstrated by a study of the Middle Fork of the Vermillion River (Stall and Yang 1972). Measurements of area of flow, roughness coefficients, width, depth, velocity, and slope were made on a 3360 feet test reach containing three riffles and two pools. Measurements were made at low, medium, and high discharges and USP was calculated for the natural stream and an "equivalent" channel without pools and riffles (Table 7). USP was reduced by 23-26% in a pool and riffle stream during medium and low flow conditions when compared to an equivalent uniform channel of the type normally formed by present channelization practices. Pools and riffles served as an effective means for the channel to reduce USP and its erosive energy and sediment transporting capability during low and medium flows. At high flows the pools and riffles were obscured and had no effect on stream gradient or USP (Figure 11). Unfortunately, suspended sediment concentrations were not measured and similar types of data were not collected for an area of pools and riffles in conjunction with meandering.

TABLE 7. UNIT STREAM POWER FOR THREE FLOW CONDITIONS, MIDDLE FORK VERMILLION RIVER NEAR OAKWOOD (Modified from Stall and Yang 1972)

Flow		Unit Stream Power (foot-pounds per pound per second)		
Amount Q (cfs)	Frequency F (% of days)	Pools and Riffles	Uniform equivalent channel	reduction %
18.9	0.80	0.000282	0.000382	26.2
43.6	0.60	0.000452	0.000589	23.3
681	0.15	0.002526	0.002522	0

However, data collected at Black Creek (Karr and Gorman 1975) relating suspended sediment concentrations to stream morphology correlates well with the results of Stall and Yang (1972). Karr and Gorman measured suspended solid concentrations in a channelized section above a forest, a meandering pool-riffle section within forest and a channelized section below forest. The meandering pool-riffle section acted as a sediment trap during low and medium flow conditions, resulting in a decrease of 28% in suspended solids by the time the flow reached the lower end of the forest (Fig. 12). This reduction is similar to the reduction in USP caused by pools and riffles shown in Table 7. As the flow left the forest, suspended solid concentrations attained the same level as the channel above the forest. The roughness

(n) is the likely factor responsible for the decreased sediment loads since the slopes (S) are lower (.25) above and below the woodlot than in the woodlot (.40).

We conclude that sediment reduction in the Karr and Gorman study results from the effect of channel morphology instead of the impact of the near stream biota, at least under normal flow regimes. However, during periods of high runoff, the forest or other vegetation along the stream might act in conjunction with the stream morphology to improve water quality. To separate the effect of these two variables, one would have to compare streams with and without vegetative filters along a major portion of their drainage length, rather than a mere patch of natural vegetation as observed by Karr and Gorman. Such a comparison should be made for a wide variety of flow regimes.

At very high flow rates (100 yr. storm) no reduction in suspended sediment concentrations occurred at Black Creek, probably because pools and riffles were obscured and no reduction in USP occurred. This result, which is similar to the result of Stall and Yang (1972), suggests that knowing the flow (Q) at which no reduction in USP occurs and its frequency (F), one could predict what fraction of the year pools would act as sediment traps.

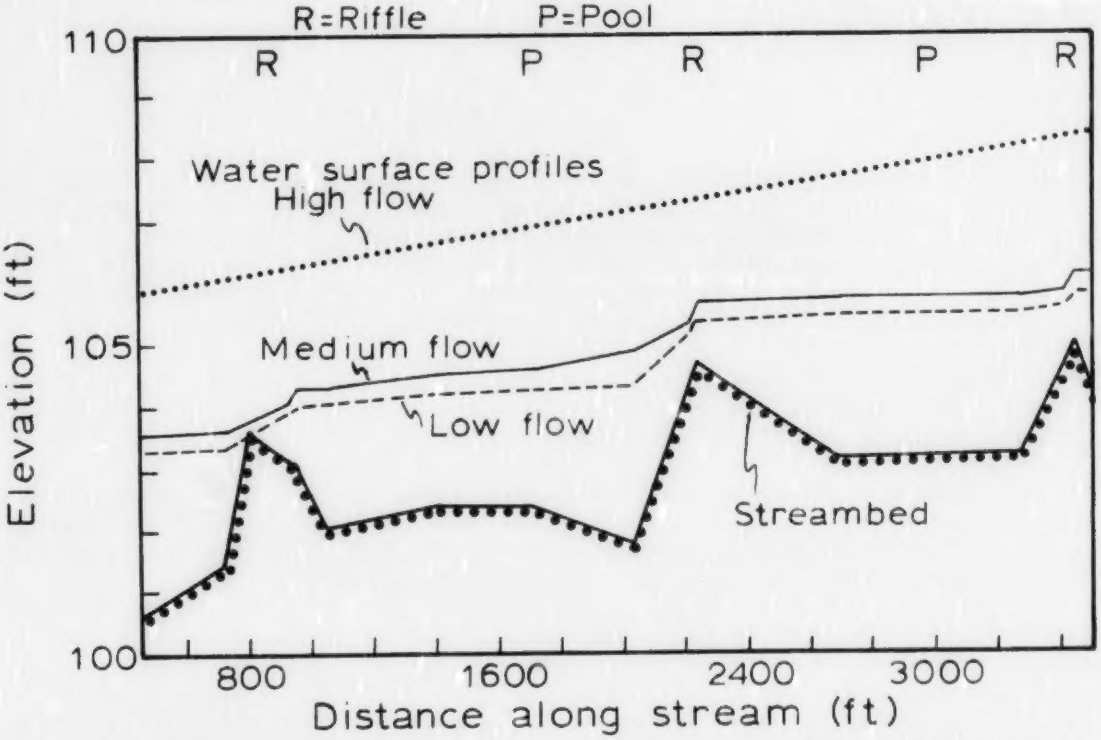

Figure 11. Bed and water surface profiles for several flow conditions in the Vermillion River. Note that the pool and riffle character of the stream is obscured as flow volume increases. (Modified from Stall and Yang 1972)

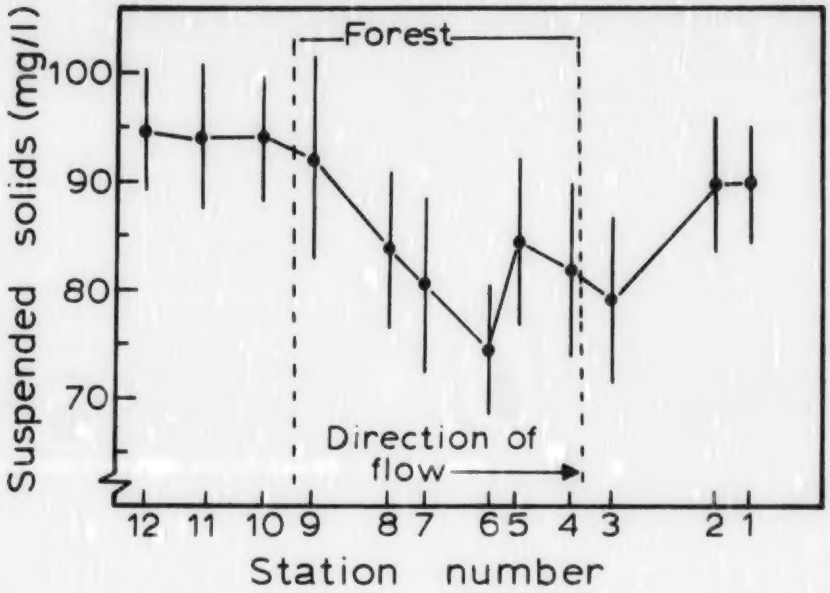

Figure 12. Changing suspended solids loads in agricultural and forested sections of a headwater stream. Dashed lines indicate margin of forest. High sediment loads at station 5 are due to an erosion problem at the outlet of a field tile. Data from July 1974 to October 1975. Sample size varies from 12 to 16 at each station. (Modified from Karr and Gorman 1975)

From this brief review of the literature and data relevant to the relationship between the "manageable" parameters of stream morphology and their effects on water quality, four critical points have been established:

1. A stream naturally decreases its USP and sediment transporting capability by increasing its bed roughness and by making lateral (meandering) (Hussey and Zimmerman 1953) and vertical (pools and riffles) adjustments (Yang 1971a,b, Stall and Yang 1972).

2. USP is reduced by pools and riffles only at intermediate and low flows.

3. The effect of meanders on USP in conjunction with pools and riffles at various flow rates does not appear to have been quantified.

4. Channelization in agricultural areas destroys nearly all characteristics of "natural" stream morphology. As a result USP is increased

and the ability of the stream to transport sediment and erode its banks is enhanced.

These four points, along with the data of Karr and Gorman (1975), indicate that allowing streams to maintain their natural morphology or allowing them to reinitiate meandering to reduce USP and suspended sediment concentrations is a feasible management alternative for improving water quality, especially during periods of low and intermediate flows. During these periods pools act as sediment traps to reduce suspended sediment concentrations and increase the suitability of the water for human uses. The overall effect on aquatic organisms needs more detailed investigation.

This raises the question: Are materials deposited in low flow periods flushed downstream during later storm events? The quantity of material reaching the final sediment trap such as a lake or reservoir would not be affected (unless of course stream bank erosion is a major sediment input) but the sequence of input would be altered. Instead of a continual input into the lake or reservoir, trapped sediment inputs would be restricted to high flow periods when pools are flushed (Lane and Borland 1954, Straub 1942). The effect of flushing versus a continual input of attached nutrients may have significant implications for nutrient dynamics in the receiving body of water, especially during low flow periods in mid and late summer when nutrient concentrations are frequently reaching limiting levels for algal uptake. Furthermore, the nutrients attached to the sediments trapped during these periods may have their eventual avilability altered by aquatic invertebrates (Davis 1974) before being flushed into the lake or reservoir. Also, flushing of the sediment versus a continual input may have a significant effect on the fraction of sediment trapped by the lake or reservoir via decreasing its detention time (Rausch and Heinemann 1975). All of these possibilities should be examined by more detailed research on (1) the quantity of sediment trapped by the stream, (2) the size fraction of sediment trapped by the stream, (3) timing of sediment transport, and (4) the biological and physical interactions involved both on the stream bottom and in the lake.

However we feel the main benefit, with respect to water quality, from a more natural stream morphology would be a substantial reduction in the suspended sediment concentration in a stream during low and intermediate flow periods, resulting in monetarily important improvements in water quality. The costs of such a management practice would include (1) taking some land out of production to maintain a natural meandering channel and (2) the economic effect of decreasing the rate of land drainage. Rough estimates for (1) could be obtained by using one of the empirically determined relationships between meander amplitude and channel width (Leopold and Wolman 1960, Leopold et al. 1964). One should expect a large error in this type of estimate (see Leopold et al. 1964). Determining the possible effect of decreasing the rate of land drainage (#2 above) may also be difficult. However, if natural stream morphology was used in conjunction with a vegetative filter along the streambank and high quality tile lines were maintained any detrimental effects would probably be minimal, especially in light of the length of time (4-6 days) corn and soybeans can withstand flooding (Hamilton 1969).

SECTION 7

DETERMINANTS OF SEDIMENT LOADS IN FLOWING WATERS

As noted in the introduction to this review early efforts in the soil conservation field emphasized the control of erosion to insure the maintenance of the productive capacities of soils. Recently, conservationists have recognized that meeting this objective does not necessarily result in maintenance of water quality. For example, in many situations soil losses of 5 tons/acre are tolerable as the soil replaces itself at that rate. Although that loss from the soil may be tolerable, the addition of 5 tons/acre into flowing waters has serious consequences for water resources. As a result of this problem, conservationists are attempting to develop a set of water quality criteria.

The theoretical foundation for calculation of soil loss is the Universal Soil Loss Equation (USLE). The present form of the equation is a result of more than 20 years of research by many scientists (Wischmeier and Smith 1965). It has remained relatively unchanged for the past decade.

The equation is used by agriculturists to predict the average soil loss in tons per acre per year. This is compared to the "soil-loss tolerance", the maximum rate of erosion that will result in sustained production indefinitely. This model is presented in the form of an equation:

$$A = R\ K\ L\ S\ C\ P.$$

Each of the terms of the equation are defined and discussed briefly below. For more detailed discussion of the model and its use, the reader is referred to Agriculture Handbook No. 282 (Wischmeier and Smith 1965).

Computed Soil Loss (A). The average soil loss in tons per acre per year as computed from the six factors of the Universal Soil Loss equation.

The Rainfall Factor (R). This is the number of erosion-index units in the average year of rain. An erosion-index unit is a measure of the erosive force of specific rainfall reflecting the combined effect of rainfall impact to dislodge soil particles and runoff to transport dislodged particles.

The Soil-Erodibility Factor (K). This component of the equation measures the susceptibility of the soil to erosion. Since erodibility varies with slope, cover, management, and other factors it is essential that erodibility be measured under controlled conditions. Generally, it is expressed as a relative value for a specific soil in cultivated continuous fallow on a 9% slope 72.6 feet long. Soil characteristics which affect the K-factor include, among others, infiltration rate, permeability and total water-holding capacity.

The Slope-Length Factor (L). This is the value obtained by computing the ratio of soil loss from a field of any length to that of a standard field with a length of 72.6 feet. Soil type and gradient are assumed to be constant.

The Slope-Gradient Factor (S). This is the ratio of soil loss from the field to that from a 9% slope, other factors held constant.

The Cropping Management Factor (C). The factor C in the soil-loss equation is the ratio of soil loss from land cropped under specified conditions to the corresponding loss from tilled, continuous fallow. This factor attempts to evaluate the combined effect of cover, crop sequence, and management practices. Crop residues may be left on the surface, removed, chopped, or plowed under. Crops may be grown continuously or rotated in various combinations. These and other variations in land management which change erosion rates are incorporated into factor C.

The Erosion-Control Practice Factor (P). The factor P is the soil loss with various practices relative to soil loss with straight-row farming, up-and-down slope, contour tillage, stripcropping on the contour, terrace systems, and stabilized waterways are the most important practices involved in the P factor of the USLE. A number of practices such as improved tillage regimes, sod-based rotations, and fertility treatments contribute to erosion control, but these are considered conservation cropping and management practices. They are, therefore, incorporated in the factor C discussed above.

Recently, a number of studies (Stall 1964, Karr and Gorman 1975, Great Lakes Basin Commission 1976) have shown that the USLE may not be useful in predicting the sediment transported by a stream or river. A regional analysis of lakes and watersheds in central Illinois showed a predicted soil loss of 3.2 tons/acre, while deposition in lakes averaged only about 1 ton per acre per year (Stall 1964). The proportion of the eroded soil that reached the lake bed varied among lakes from 10 to 50%. In the Maumee River Basin only about 11% of total erosion is yielded annually as suspended sediments to Maumee Bay (Great Lakes Basin Commission 1976). Clearly, much of the material eroded from the land surface, using the assumptions of the USLE, does not reach lakes or reservoirs.

This raises the question of where the sediments are deposited. Perhaps they are deposited in the channels of the streams and rivers that flow into the lakes. Perhaps the soil is deposited on the land surface before it reaches the stream or on the banks of the stream. Or if it is in fact reaching the lake, it may be carried out by the discharge water.

Alternatively, the techniques for measuring and calculating amounts of sediment deposited in the lake or reservoir may not be accurate. In the following discussion we shall comment on the problems associated with each of these possibilities.

1. Errors in calculating volumes of lake sediment. There certainly is some error associated with this factor but it is probably minor when compared to the range of variation observed among lakes.

2. Sediment removed from lakes by discharge water. The potential for error here is larger. No doubt some small particles move downstream by this route. Variables that might be considered here include the size, turnover time, and cross-sectional area of the lake (Rausch and Heinemann 1975). Long, narrow lakes or small lakes might have rapid flowthrough rates which result in considerable fine particle material being carried out of the lake before it is deposited. However, as Stall (1964) reported, a large share (39%) of the sediment in lakes is clay, suggesting that much of the fine material is deposited in the lake bed. In summary, there is reason to believe that this factor may be of some significance in the variation among lakes but more careful study is needed.

3. Soil deposited on land surface at varying distances from the channel. This problem is certainly dealt with in the USLE in the form of erosion control practices (P). However, a larger problem is the difficulty involved in scaling differences between models and the real world. For example, erosion determined from study of a small plot can only approximately be expanded to very large areas. The problem is even more complex when the larger area has a diversity of slopes, for example, and includes some pockets from which there is no outlet except percolation down through the soil. Furthermore, even small discontinuities such as fence rows, field borders, concave vs. convex slopes as the floodplain is approached (Young and Mutchier 1969) are commonly not incorporated into USLE determinations. This general factor--sediment deposition before runoff reaches the stream--needs more investigation and is the larger class in which greenbelts should be included.

4. Deposition in the stream channel. Recognition of this possibility stimulated the excellent research of Stall and Yang that resulted in the idea of Unit Stream Power to predict suspended sediment concentrations. As discussed above (Section 6), this theory suggests that sediment concentration is an increasing function of unit stream power (Figs. 10 and 13), and the variation in suspended sediment loads for a given stream power should be low (Fig. 13, stippled area). As is often the case, the real world is only a rough approximation to the theory. For any USP there is commonly considerable variation in sediment loads (Fig. 13, cross-hatched area). That is, sediment concentration is an increasing function of energy in the stream, which is an incresing function of USP. This is true as long as a myriad of other factors are held constant: stability of bank, erodibility of soils, bedload availability, variation in land use, and many others. A different line could be necessary in Fig. 13 for each such factor, therefore accounting for the variation in sediment load with USP which is frequently observed.

Clearly, the unit stream power concept is useful but some variation in sediment loads is unaccounted for when this model is used. An example will illustrate the weaknesses of the single factor approach of USP to account for variation in sediment loads. Two identical forested watersheds are contrasted in the following way: one is cleared of forest and planted with a row crop such as corn, while the second is left as a forested control. The streams in these two watersheds would carry markedly different sediment loads despite identical unit stream powers. Clearly, velocity will vary due to differing runoff rates but the general point here is that with the same slopes and at similar flow rates sediment loads will not be the same in the two streams.

What is needed then is a model, analogous to the universal soil loss equation, which will predict sediment loads for a flowing stream. This model, dare we call it the Universal Sediment Load Model (Equation), must consider a complex of factors. It is too early to specify all the parameters of this model. However, the previous discussion and comments in following sections show that the situation is more complex than the Universal Soil Loss Equation might lead us to believe. Among other things a realistic sediment model must consider the magnitude of erosion from a watershed, how and where eroded material is removed before runoff reaches waterways, and the addition of sediment from underground (drain) tile systems. Finally, as discussed in a later section, the nature of the erosion-deposition equilibrium between the terrestrial and aquatic environments must be clearly understood.

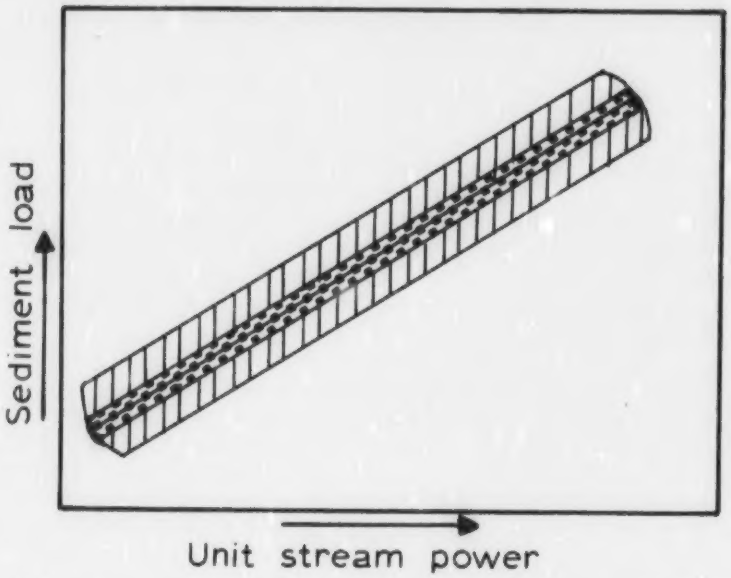

Figure 13. Variation in suspended sediment load for a given unit stream power (see text for explanation).

SECTION 8

EFFECT OF STREAMSIDE VEGETATION ON WATER TEMPERATURE

This report has emphasized the feasibility of using vegetation along streams to reduce sediment and nutrient inputs into agricultural drainages. Another potential use of this vegetation is to control water temperature. Past evaluations of the effect of streamside vegetation on water temperature will be reviewed here, along with an examination of the significant effects of temperature on dissolved oxygen levels and nutrient dynamics, especially the release of nutrients from sediments and their uptake by nuisance algae and periphyton. The importance of water temperature in maintaining a "fishable" water quality will be discussed in a later section of this report.

Because of the importance of temperature in regulating the physical and biotic characteristics of streams, a number of studies have documented the effect of streamside vegetation on water temperature. Green (1950), in a study at the Cowetta Hydrologic Laboratory, documented the effect of land use on water temperature. For a period of one year he compared the temperature of a stream on a farm which had originally supported a hardwood forest but for eight years had been under cultivation and pasturage and that of a stream in mature hardwood forest (Fig. 14). The weekly maximum temperatures of the farm stream ranged from 5.0 to 12.8°C above the forest stream (average 6.4°C). Both streams were coldest during the month of February but the temperature of the forest stream frequently ranged as high as 3.9°C above the farm stream. Similar effects of vegetation on temperature extremes were found in studies of a stream before and after vegetation was removed from the streambank (Gray and Eddington 1969). In another study, stream temperatures inside a small woodlot (19°C) were much lower than in unshaded areas (28°C) nearby (Karr and Gorman 1975). These data indicate vegetation serves as an effective buffer against temperature extremes; shaded streams are cooler in the summer and warmer during winter.

A more detailed analysis of the result of several types of land treatment on stream temperature was performed in the Appalachian Mountains (Swift and Messer 1971). Clear-cut streams averaged (5.5-6.5°C) warmer than forested streams. During periods of highest temperatures, temperature minimums were also increased. This indicates that the streams did not have a "normal" cooling-off period during the night and that periods of elevated temperatures may be prolonged. Long-term elevations in temperatures can have significant effects on the energetic "balance sheet" of aquatic ecosystems, resulting in major alterations in their biotic components. From a management perspective, one other important observation was made by Swift and Messer. If streamside vegetation was left to shade the channel, while the

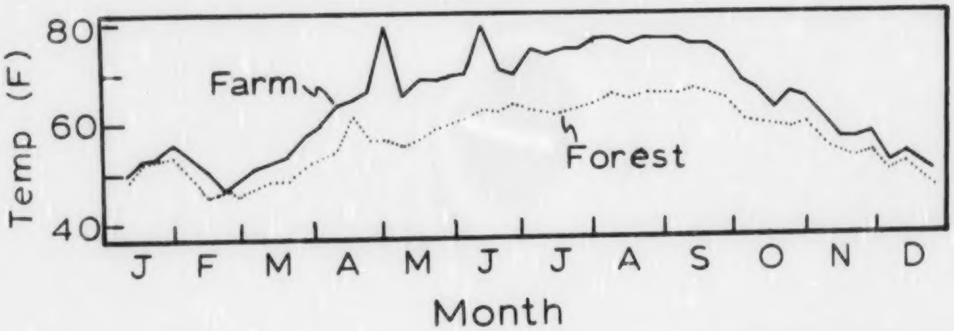

Figure 14. Seasonal changes in water temperatures of streams from forested and farm watersheds (From Greene 1950).

rest of the woods was clearcut, only minor changes in stream temperature were observed. This latter point suggests that if a minimal vegetative "buffer strip" is left along agricultural drainages, significant decreases in stream temperature and improvements in water quality could be expected.

More recently, a detailed analysis of the use of "buffer strips" to control temperature has been made in the field of forestry (Brown and Brazier 1972). Previous mathematical analyses by Brown (1969) and Brown and Krygier (1970) demonstrated that net thermal radiation in relation to stream discharge was the primary determinant of stream temperature. When strips of brush or trees were left along the stream, no increase in temperature occurred. From an economic and management perspective it is therefore desirable to know whether controlling the temperature of the stream is a function of the volume of vegetation in the buffer strip, the strip width, or the density of the canopy of the strip which is perpendicular to the suns rays. An extensive examination of temperature in various streams with different types of buffers indicated that angular canopy density (ACD - a measure of the shading ability of the vegetation) is the only buffer strip parameter correlated with temperature. The generalized relationship between ACD and heat input into a stream is illustrated in Figure 15. Buffer strip width was not important. A buffer strip 5-10 feet wide was as effective at temperature control as a strip 50 feet wide, as long as its ACD was high. Brown and Brazier (1972) also observed that buffer effectiveness decreased with increasing stream size (Figure 16). Small streams have the greatest temperature problem but they are also the easiest to control, due to the inverse relationship between temperature change and stream discharge for a given input of thermal radiation. These results indicate that little or no land would need to be taken out of production for temperature control on small streams. Further, natural processes will provide sufficient ACD levels on small streams through succession as cottonwoods, willows, or other types of vegetation invade the stream banks. Finally, if temperature control is accomplished in the upper reaches of drainages, a reduction in temperature associated problems will result in upstream areas as well as in downstream areas, including small lakes and reservoirs.

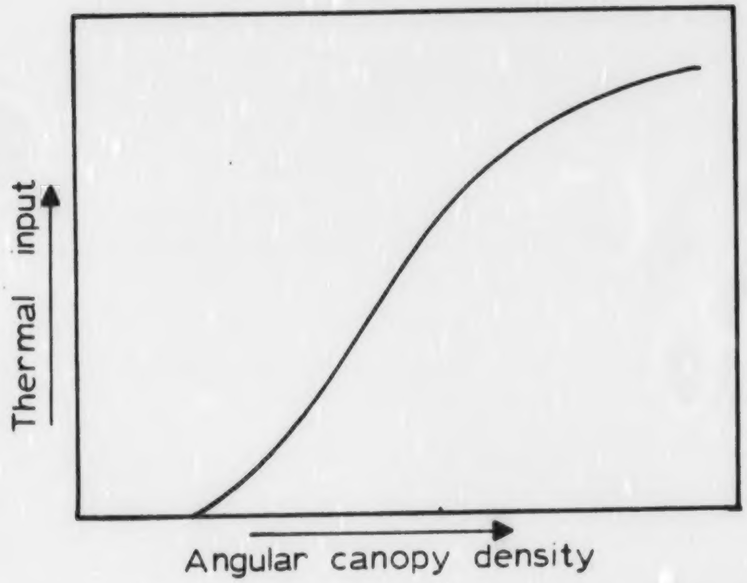

Figure 15. Hypothetical relationship between angular canopy density and thermal input to streams (Modified from Brown and Brazier 1972)

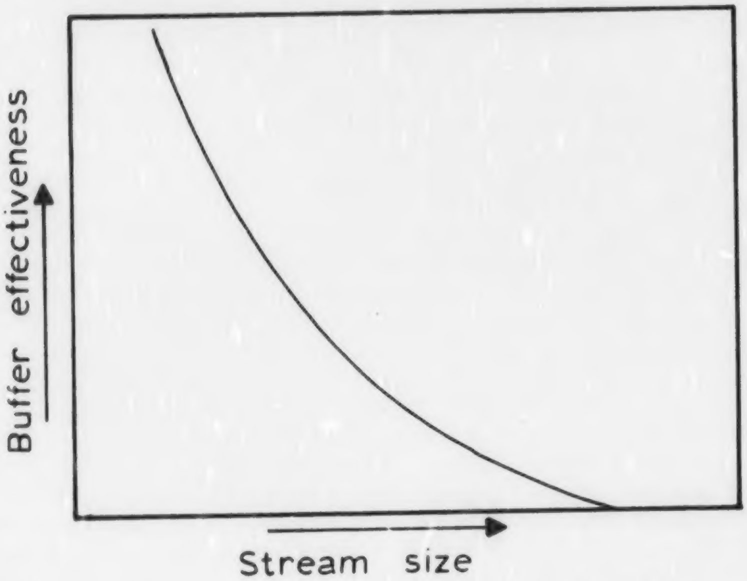

Figure 16. Relationship between stream size and effectiveness of buffer strip in reducing thermal inputs to a stream (Modified from Brown and Brazier 1972)

The importance of temperature in determining various water quality parameters and regulating biotic communities cannot be overemphasized. As temperature increases, the capacity of the water to hold oxygen decreases (Table 8). Since oxygen is utilized during the decomposition of organic matter, at elevated temperatures the ability of the stream to assimilate organic wastes without oxygen depletion is reduced. This exaggerates the impact of each additional unit of waste added to the system.

TABLE 8. RELATIONSHIP BETWEEN TEMPERATURE AND MAXIMUM DISSOLVED OXYGEN CONCENTRATION IN WATER

Temperature °C	Maximum oxygen concentration (ppm)
0	14.6
10	11.3
20	10.7
30	7.6

Even more important with respect to water quality and eutrophication is the effect of temperature on the release of nutrients from sediments. Sommers et al. (1975b) studied the effect of incubation temperature on soluble nutrient concentrations. They found significant effects of temperature on the rate at which insoluble (attached nutrients) were converted to soluble and readily available forms. Figure 17 illustrates the relationship between temperature and amount of phosphorus released from the sediments in a 12-week period. This plot indicates an exponential increase in phosphorus released with an increase in temperature. Slight increases in temperature above 15°C produce substantial increases in the amount of phosphorus released.

These data, along with those previously discussed, indicate that by removing vegetation which shades agricultural drainages, several detrimental patterns will develop: (1) Increases in temperature will occur during summer periods (5.5-9.0°C), resulting in increasing rates of phosphorus disassociation from sediments. (2) Increases in phosphorus concentrations in the drainages result in higher nutrient concentrations in receiving bodies such as lakes and reservoirs. (3) Increasingly large blooms of nuisance algae and periphyton will appear because of elevated nutrient concentrations, temperatures, and light availability. The effect of all these will be to decrease water quality and the quality of biotic communities.

The importance of streamside vegetation clearly goes beyond its use in filtering sediments and nutrients from surface runoff. Its potential for temperature control, enhancement of the oxygen carrying capacity of the stream, and reducing nutrient availability and utilization is evident. Its significant economic impact on fishery resources will be discussed in a later section of this report. These benefits appear to outweigh the negligible cost of this management practice. Little or no land would have to be taken out of production and natural processes would provide the vegetation for shading the streams by processes of natural succession. To fully evaluate this management alternative, more detailed analyses of its benefits to water quality and the stream biota in relation to the cost of decreased rate of drainage must be performed.

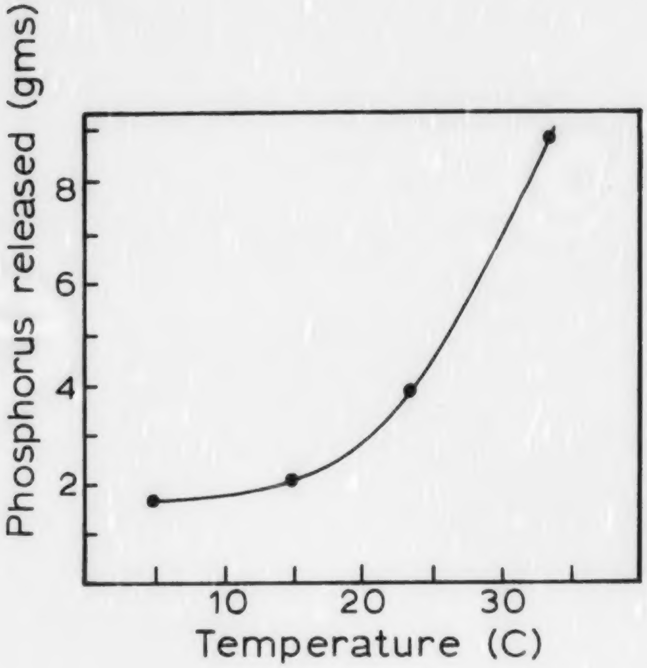

Figure 17. Effect of temperature on the release of phosphorus from sediments over a 12-week period (Data from Sommers et al. 1975b).

SECTION 9

IMPACT OF NEAR STREAM VEGETATION AND CHANNEL MORPHOLOGY ON STREAM BIOTA

Streams may be narrowly viewed as a means for transporting water away from the land, as collecting points for a water supply, or as outlets to carry away the refuse of modern society. This combination of uses relates to the needs for water quality and is therefore relevant to the subject of greenbelts--especially when increasing demands are being placed on resource managers to improve the biological aspects of environments and to provide areas suitable for use by an increasingly recreation oriented public. This trend is demonstrated by the federal government's call for "fishable and swimmable" water by 1983. Therefore, alternatives proposed for controlling non-point pollution from agricultural areas must also be evaluated in light of their effects on the biota of streams and on recreational opportunities.

A surprising fact to most non-biologists is that small headwater drainages in agricultural watersheds are extremely important in maintaining fishable populations (sport and commercial) in larger streams, rivers, or lakes. They are important as breeding grounds for many valuable species which migrate into these areas from lakes or large rivers to spawn (Hall 1972, Smith 1972, Karr and Gorman 1975). Also, they serve as breeding grounds and/or permanent habitats for the smaller fish used for food by these species. If these environments are disrupted or destroyed, a major source of food for the commercially valued species will be destroyed and many of the valued species will be prevented from reproducing. This happened in the Lake Erie basin and was one of the major causes of the destruction of a multi-million dollar fishery in that region (Regier and Hartman 1973, Smith 1972, Ryder and Johnson 1972).

In this section we briefly examine the effects on the biota in headwater streams of (1) elevated sediment loads, (2) increased water temperature due to removal of vegetation along stream banks, (3) disruption of the aquatic food chain by removal of allochthonous (terrestrial) inputs of energy, and (4) decreased habitat diversity due to stream channelization. With this information we then evaluate the potential of greenbelts for improving the biological quality of streams. In Section 10 we briefly outline some of the possible recreational benefits of greenbelts.

EFFECTS OF SEDIMENT

Fish

Most research on the effects of sediment on fish emphasizes commercially important species such as the salmonids. For adult fish only very high concentrations of sediment ($>$20,000 ppm) cause mortality, primarily by clogging the opercular cavity and the gill filaments (Wallen 1951). This prevents normal water circulation and aeration of the blood. Such high sediment levels are rarely encountered in streams.

However, indirect effects on adults may occur at much lower sediment concentrations. In areas with slightly increased suspended solids loads (35 ppm) adult cutthroat trout showed no increase in distress or mortality, but the fish did cease feeding and move to cover (Bachman 1958 cited in Cordone and Kelly 1961). Similar subtle changes in behavior were noted in smallmouth bass and green sunfish when turbidities were elevated (14-16 JTU) for 30 days (Heimstra et al. 1969). Furthermore, the normal social hierarchy was disturbed with elevated turbidities. When in search of spawning areas, adult salmon swim through areas of high turbidity in search of clear areas for spawning (Cooper 1956). These results suggest that adult fish tend to be physiologically resistant to the direct effects of elevated sediment levels but that their behavior can readily be altered by only slight increases in turbidity levels (Swenson et al. 1976).

The major effect of sediment on fish populations is the disruption of normal reproduction (Cordone and Kelly 1961). When sediments settle out of suspension they frequently cover essential spawning grounds of fish, cover eggs, or prevent emergence of recently hatched fry. One of the earliest experiments to document the effects of sediment on egg survival was that of Harrison (1923, Table 9). As the particle sizes in the bottom decrease, the survival rate of eggs declines. A number of other studies have documented similar effects of sediment on egg survival and fry emergence (Shapavalov 1937, Shapavalov and Berrian 1940, Shapavalov and Taft 1954). The cause of the reduced survival is a decrease in circulation of water around the developing eggs, resulting in the inhibition of oxygen uptake and carbon dioxide release. This results in reduced metabolic rates which are lethal if inhibition is prolonged (Snyder 1959). Thus, the effect of sediment on spawning success has been one of the major causes for the decrease in the quality of fisheries throughout the United States and has prompted some (Langlois 1941) to suggest that changes in bottom type are of utmost importance in modifying the breeding grounds and determining fish diversity. As bottom type is simplified by the deposition of sediment, species diversity decreases. Recent research (Gorman and Karr 1977) suggests a direct relationship between species diversity and bottom diversity (Fig. 18). However, the low correlation coefficient suggests that other factors are also important in determining species distributions. As will be pointed out below, the effect of sediment on bottom type is only one of several physical factors which interact to determine the structure of fish communities in streams. Thus, the single problem-single solution approach frequently used in the past (e.g. reduction in sediment inputs to improve fisheries) will have limited usefulness for improving the quality of the stream biota.

Invertebrates

Many aquatic invertebrates spend a large proportion of their life on or in the bottom substrate. Sediment deposition, resulting in decreased

TABLE 9. THE EFFECTS OF PARTICLE SIZE OF SUBSTRATE ON EGG SURVIVAL IN SOCKEYE SALMON (*Oncorhynchus nerka*) (From Harrison 1923).

Number of eggs planted	Description of Nest	Number of eggs hatched
500	Large gravel, very little sand, no clay or top covering of silt	420
500	Small gravel, some clean sand	350
500	Small gravel, top coating of silt 1/2 inch deep	325
500	Very fine gravel, sand, and small amount of clay in sand	200
500	Very fine gravel and much clay or mud in sand	170

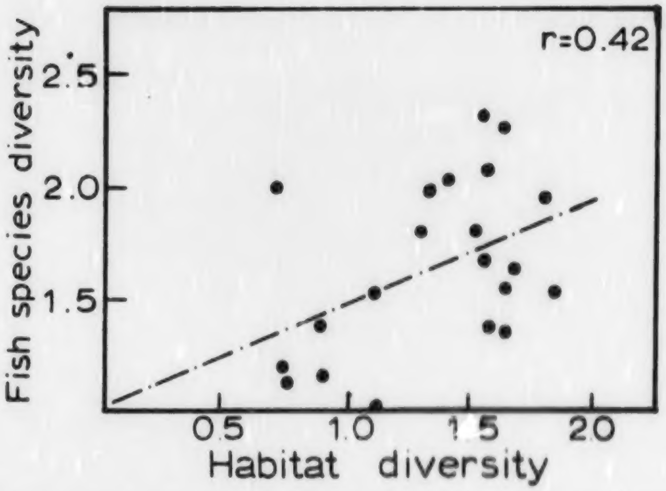

Figure 18. Regression of fish species diversity on substrate diversity (From Gorman and Karr 1977).

substrate types, will inevitably cause changes in the species diversity and numerical abundances of benthic organisms (Ellis 1931, Tebo 1955, Wilson 1957). Commonly these changes can be related to changes in substrate diversity (Smith and Moyle 1944, Harman 1972, Fig. 19). There is a general relationship between substrate diversity and species diversity of molluscs but the scatter, as in the fish data discussed above, suggests other environmental variables are also important. Other studies have shown the importance of depth diversity and water velocity (Zimmer and Bachman 1976), temperature (Sprules 1947) and organic inputs from terrestrial environments (Ross 1963, Woodall and Wallace 1972, Cummins 1975) in determining the distribution and abundance of aquatic invertebrates. Clearly, reduction in sediment inputs must be accompanied by improvements in other water quality characteristics for maximal benefits to invertebrate populations.

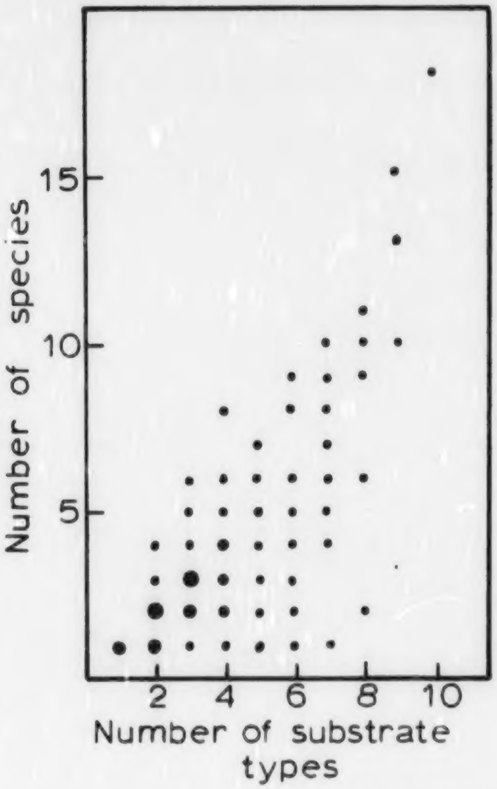

Figure 19. Species diversity vs. substrate diversity for molluscs collected at 650 sampling stations in New York. Size of dots proportional to density of observations. (From Harman 1972).

Stream Productivity

The discussion of the effects of sediment on fish and invertebrates makes it clear that with increasing sediment loads, productivity in aquatic ecosystems will often decline. A comprehensive study of the energetics of Red Cedar River in Michigan showed that stream productivity declined significantly following siltation (King and Ball 1967). When turbidity levels shifted from 20-30 JTU to 380 JTU, Aufwuchs production declined by 68% and heterotrophic energy consumption declined by 58% (Table 10). Sediment increases resulted in reduced ecosystem productivities across all trophic levels.

TABLE 10. ENERGY BUDGETS FOR THE RED CEDAR RIVER BEFORE AND DURING PERIODS OF HEAVY SILTATION, SUMMER, 1961. Units are cal m^{-2} day^{-1} (King and Ball 1967)

Trophic level	Energy fixed	
	Before siltation	During siltation
Autotrophic Aufwuchs	1,140	368
Macrophytes	127	127
Total primary producers	1,267	495
Heterotrophic Aufwuchs	360	170
Insects:		
Herbivores (net yield)	43	-9
Carnivores (net yield)	13	6
Tubificid worms	65	-39
	Energy Required	
Heterotrophic Aufwuchs	4,000	1,889
Total insects	283	4
Tubificid worms	200	-115*
Total energy required	4,483	1,893

*Negative values are not included in the total energy required.

Summary

Clearly, the impacts of sediments on the stream biota include alteration of the structure and productivities of plant, invertebrate, and vertebrate communities. Reductions in sediment loadings will improve the biota of streams but, as we will demonstrate below, more comprehensive management programs will be necessary to improve stream biotas; that is, efforts to reduce sediment loads must be accompanied by more informed management of other stream characteristics.

EFFECTS OF TEMPERATURE

Temperature has a significant effect on oxygen concentrations and nutrient dynamics within streams (see pp. 44). Elevated temperature, due to the removal of vegetation along stream banks, increases the susceptibility of biological systems to inputs of nutrients and other pollutants. Temperature changes, regardless of other physico-chemical changes, may also cause shifts in the entire structure of aquatic communities.

A clear understanding of this problem depends on knowledge of the energetic processes of organisms. The use of energy by an organism can be represented by a flow chart (Figure 20). Energy is ingested but only a fraction of what is ingested is actually available to the organism as net energy for utilization. This net energy must then be divided among standard metabolism (maintenance of body functions), active metabolism (providing energy for swimming, feeding, etc.), growth, and reproduction. The ability of an organism to survive and reproduce is dependent on the organism being in an environment where some fraction of energy input is available for growth and reproduction.

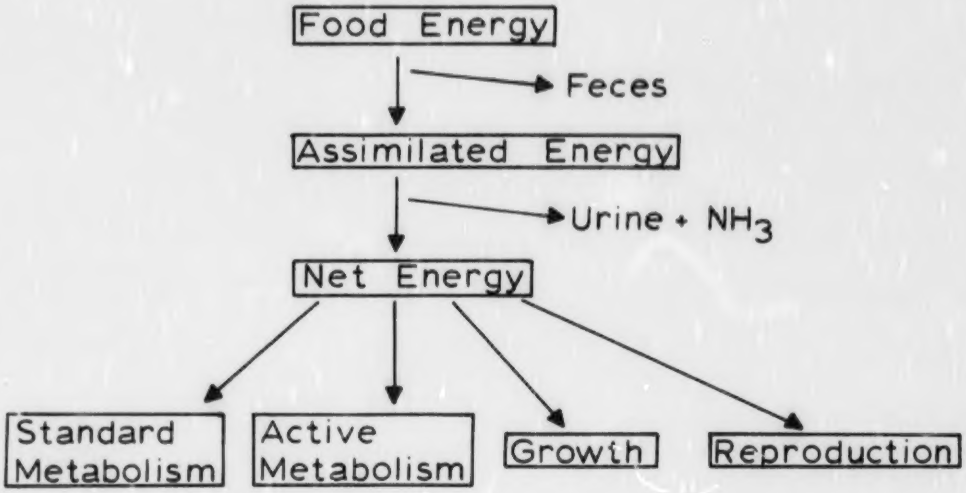

Figure 20. Flow chart illustrating the basic pathways of energy flow in organisms.

Because fish are cold-blooded organisms (poikilotherms), temperature is extremely important in determining their standard metabolic rate (Brett 1972). As temperature increases, standard metabolism increases but other factors, such as feeding rates (energy intake), also increase. As a result, each species has an optimal temperature for feeding, general activity, growth, and reproduction. This can be illustrated by comparing two hypothetical fish species (Figure 21). For both species, activity, food consumption, and in turn growth, decrease at temperatures below the optimum. At temperatures above the optimum, food consumption starts to decrease but more importantly, increasing standard metabolism demands more and more of the energy value of the food with less being available for growth and reproduction. This is of course a very simplified explanation of the effect of temperature on the growth of fish. Numerous other factors such as food availability, age of the fish, and oxygen concentration will affect the exact form of the relationship. A more detailed discussion of these variables can be found in Warren (1971) or Brett (1964, 1970). Hypothetical species 1 (Fig. 21) has a temperature optimum of 20°C. At this temperature it has the maximum amount of energy available for growth and reproduction, while species 2 has only a minimal amount of energy available for these activities because of decreased food consumption. If the temperature of the water is increased to 25°C, species 2 would then have maximum energy available for growth and reproduction while species 1 would have little energy available because of its increasing standard metabolic requirements.

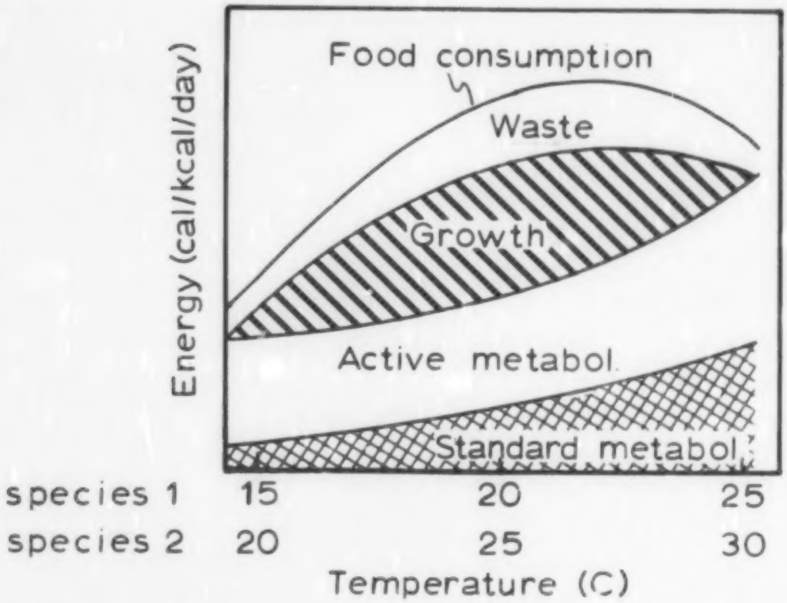

Figure 21. Theoretical effect of temperature change on food consumption and energy budget of two hypothetical fish species (Adapted from Warren 1971).

This illustrates an important point. When vegetation is removed from along streambanks and water temperatures increase from 6-9°C (Gray and Eddington 1969, Karr and Gorman 1975), it may become energetically impossible for species with lower temperature optimums to continue living in the area, regardless of changes in sediment loads, habitat structure or other environmental conditions. A shift in community structure may occur with resident species being replaced by the frequently less desirable species which are more tolerant of increased temperatures.

A common misconception is that shifts in species composition will not occur unless temperature increases are substantial, especially in warmwater streams. It is believed that since warmwater species have higher temperature optimums than species living in coldwater streams, they have a greater "assimilative capacity" for temperature increases. To test if this was true, predictions of changes in fish communities of a coldwater (Columbia) and warmwater (Tennessee) river were made based on the preferred (optimal) and lethal temperatures of their respective species (Bush et al. 1974). The percent of species lost versus temperature is shown in Figure 22. In both streams, significant individual losses start to occur after temperature changes of 5-6°C. However, as a community, the preferred temperature is closer to the lethal limit as one moves from cold to warmwater streams. Warmwater species do not have a greater assimilative capacity for temperature increases. These observations, along with a recent extensive field and laboratory study demonstrating that temperature is an extremely important factor determining the distribution of fish species (Stauffer et al. 1976), indicate that removal of vegetation along small streams will result in substantial changes in fish community composition by causing temperature changes which exceed the preferred and lethal limits for species with lower temperature optimums and favor those with higher optima and lethal limits. Similar arguments could be made for the effects of temperature on invertebrate distributions. If a major goal of present research on non-point pollution in agricultural watersheds is an improvement in the biota of streams and their "fishability," substantially more effort must be directed towards the effect of near stream vegetation on water temperature and the distribution of organisms.

EFFECTS ON STREAM ENERGETICS

Up to now, this report has emphasized the indirect impact of near stream vegetation on stream biota via its effect on sediment and nutrient inputs and temperature fluctuations. An important direct effect of the removal of this vegetation is disruption of the aquatic food web, especially in those areas where terrestrial inputs are a major source of energy for the stream.

Headwater streams (stream orders 1, 2, and 3) make up about 85% of the 3.25 million miles of running waters in the continental United States (Cummins 1975). These areas represent the maximum interface between the terrestrial and aquatic environments. It is here that most sediment enters streams and here that extensive channelization and removal of near stream vegetation is occurring. These are the areas which are most dependent on near stream vegetation for an energy source and are also extremely important as spawning and nursery grounds for many commercial and sport species which spend their adult life in lakes or large rivers (Smith 1972, Karr and Gorman

1975, Hall 1972, Hynes 1970). In these areas most of the energy utilized by the aquatic invertebrates and fish is terrestrial in origin (Cummins 1975, Lotrich 1973, Chapman and Demory 1963, Hynes 1963, Minshall 1967 - Figure 23). Once the coarse particulate organic matter (CPOM) like leaves, twigs, etc. is in the stream, either the dissolved organics leached from it are utilized or the CPOM is directly ingested by shredders which have powerful jaws to shred the organic matter and then digest the microflora growing on it. The shredders then egest a fine particulate organic matter (FPOM) which is utilized by a group of invertebrates called collectors. At the top of this food web are the fish predators.

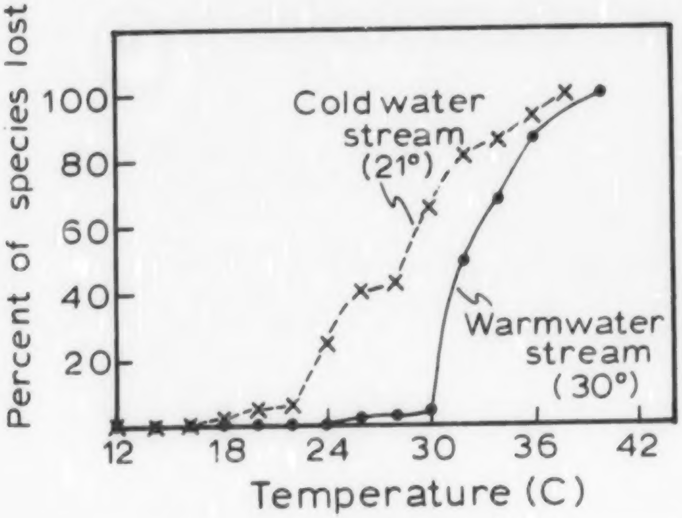

Figure 22. Percent of fish species lost versus temperature in warm and cold water streams (Data from Bush et al. 1974).

The implication of this web is that in these upstream areas removal of nearstream vegetation will result in significant reductions in invertebrate production and, in turn, fish production because of the loss of allocthonous energy inputs. Studies have indicated low diversity and numbers of invertebrates in streams flowing through areas lacking deciduous vegetation (Minshall 1968). Therefore, if we are to maintain productive fisheries in streams, we must not only maintain suitable instream habitat for the fish and their invertebrate food source but we must also maintain a major source of energy on which both invertebrates and vertebrates depend: the nearstream vegetation.

EFFECTS OF STREAM CHANNELIZATION

Channelization is one of the most detrimental factors affecting the use of streams for recreation (including fishing). The primary goals of channelization are to prevent flooding of crops and increase the amount of tillable agricultural land by allowing rapid drainage. These are desirable goals but the substantial number of detrimental effects on water quality, fisheries

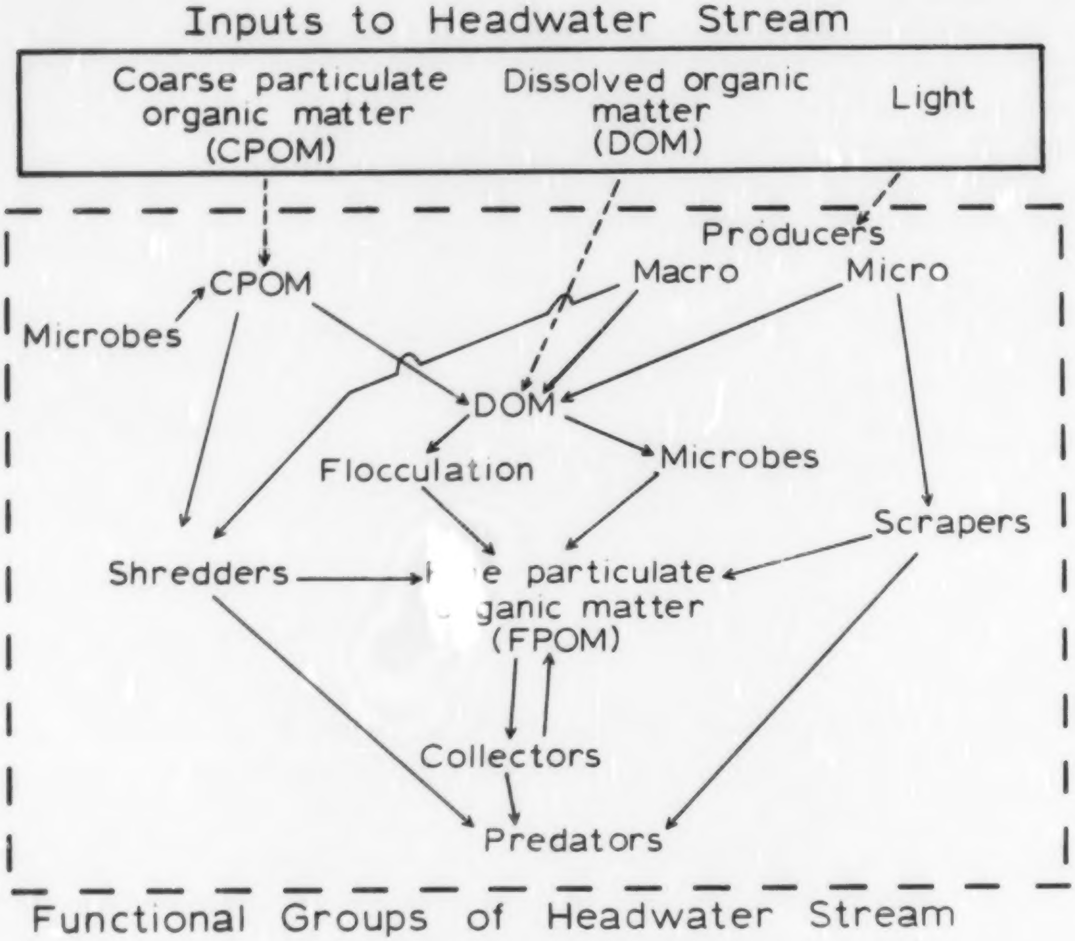
Inputs to Headwater Stream
Coarse particulate organic matter (CPOM)
Dissolved organic matter (DOM)
Light
Producers
Macro
Micro
CPOM
Microbes
DOM
Flocculation
Microbes
Scrapers
Shredders
Fine particulate organic matter (FPOM)
Collectors
Predators
Functional Groups of Headwater Stream

Figure 23. Major components of a headwater stream foodweb. Note the systems dependence on inputs of organic matter from the terrestrial environment and processing of that organic matter by stream animals (Modified from Cummins 1975).

resources, and the recreational potential of streams suggest caution in the application of technology involving channel modifications. From a number of esthetic, biological, and water quality perspectives the costs and benefits of channelization should receive a rigorous economic reevaluation. Included among its effects are (Fig. 24):

1. Increased stream temperatures and their associated problems due to removal of vegetation along stream banks (Hansen 1971);

2. Increased bank erosion (Emerson 1971) and turbidities (Hansen 1971) due to higher slopes and flow velocities, resulting in higher unit stream power;

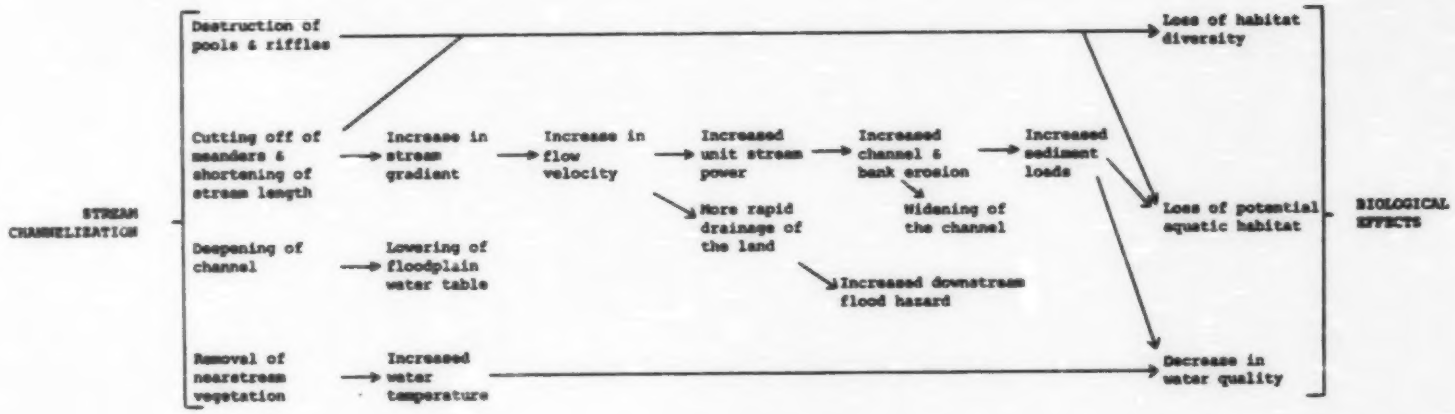
STREAM CHANNELIZATION
Destruction of pools & riffles
Cutting off of meanders & shortening of stream length
Deepening of channel
Removal of nearstream vegetation
Increase in stream gradient
Lowering of floodplain water table
Increased water temperature
Increase in flow velocity
Increased unit stream power
More rapid drainage of the land
Increased channel & bank erosion
Widening of the channel
Increased downstream flood hazard
Increased sediment loads
Loss of habitat diversity
Loss of potential aquatic habitat
Decrease in water quality
BIOLOGICAL EFFECTS

Figure 24. Factor train analysis of the effects of channelization of the physical environment and biota of streams (Modified from Darnell, 1976).

3. Increased flooding downstream (Campbell et al. 1972);

4. A reduction in habitat complexity, i.e. riffles and pools are destroyed, meanders are removed, the substrate is made uniform, and cover in the stream channel is eliminated.

One result of the synergistic action of all these effects on the physical environment is a drastic reduction in both fish and invertebrate populations. A number of studies have documented this. Congdon (1971) examined the effect of channelization on fish populations in the Chariton River in Missouri. He observed an 83% reduction in total standing crop per acre (Figure 25) and an 86% reduction in standing crop of catchable size fish per acre (Figure 26) after channelization. Bayless and Smith (1967) reported a 90% reduction in catchable size fish (over 6 inches) per acre in 23 channelized streams compared to 36 more natural streams. A 98% reduction in fish standing crop in the Tippah River in Mississippi was observed immediately after channelization (Wharton 1970 cited in Congdon 1971). Similar observations of reductions in fish populations in smaller agricultural drainages after channelization have also been documented (Karr and Gorman 1975). Other studies have demonstrated reductions in invertebrate populations due to channelization (Morris et al. 1968, Moyle 1976). For more references concerning the effects of channelization on the physical environment and fishery resources, the review by Henegar and Harmon (1971) should be consulted.

Although these studies have provided us with substantial information concerning the effects of channelization on the biota, there have been very few attempts to identify and quantify those environmental variables altered by channelization which affect the distribution and abundance of organisms. Because the main effect of channelization is the alteration of stream morphology, any relationship which can be established between morphometric variables and the habitat characteristics of aquatic organisms or morphometric variables and biological parameters should be useful in predicting the impact of channelization upon aquatic communites and should provide valuable information for improving engineering designs to minimize the biological impact of channelization (Zimmer and Bachman 1976, Menzel and Fierstine 1976, Gorman and Karr 1977).

Zimmer and Bachman (1976) examined the relationship between channel morphology, habitat diversity, and drift density of invertebrates in 11 natural and channelized streams in Iowa. They found a significant positive correlation between channel sinuosity and variability of stream depth (Figure 27a) and stream velocity (Figure 27b). The more the stream meandered, the more diverse the available habitats were with respect to water depth and velocity. In conjunction with this, they observed that as sinuosity increased (i.e. habitat diversity increased) the biomass (Figure 27c) and number of organisms (Figure 27d) in the invertebrate drift increased. These data indicate that by designing channels with more sinuosity or leaving streams with natural meanders, significant improvements in the quality of the invertebrate biota and availability of food for fish would result.

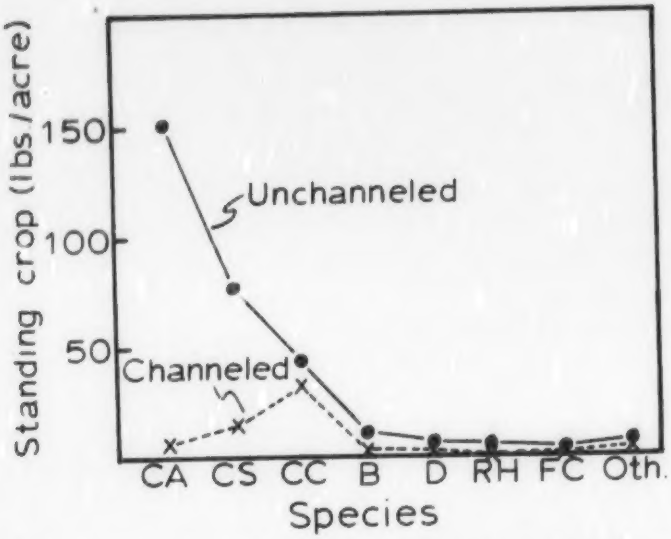

Figure 25. Estimated standing crop for fish* of unchannelized (total 304 lbs./acre) and channelized (total 53 lbs./acre) sections of the Chariton River, Missouri (Adapted from Congdon 1971).

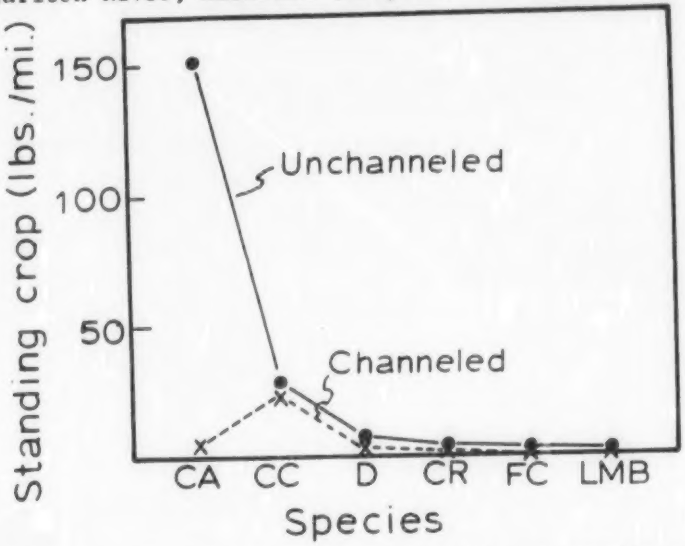

Figure 26. Estimated standing crop of catchable size fish* in unchannelized (187 lbs./acre) and channelized (total 27 lbs./acre) sections of the Chariton River, Missouri (Adapted from Congdon 1971).

*Codes for fish abbreviations:

CA - Carp (Cyprinus carpio)
CS - Carpsucker (Carpiodes)
CC - Channel Catfish (Ictalurus punctatus)
B - Buffalo (Ictiobus)
D - Drum (Aplodinotus grunniens)

RH - Redhorse (Moxostoma)
FC - Flathead Catfish (Pylodictis olivaris)
CR - Crappie (Pomoxis)
LMB - Large-mouth Bass (Micropterus salmoides)

A similar type of study (Gorman and Karr 1977) established a direct relationship between habitat diversity and the quality of fish communities. Streams were examined in three different areas and included both recently channelized and natural streams. For each sample station, fish species diversity and diversity of bottom type, depth of water, and velocity of flow were determined. The relationship between habitat diversity and fish species diversity (Figure 28) indicates fish are habitat specialists; as the diversity of bottom types, water depths, and velocity increases (or any combination of them), fish diversity increases.

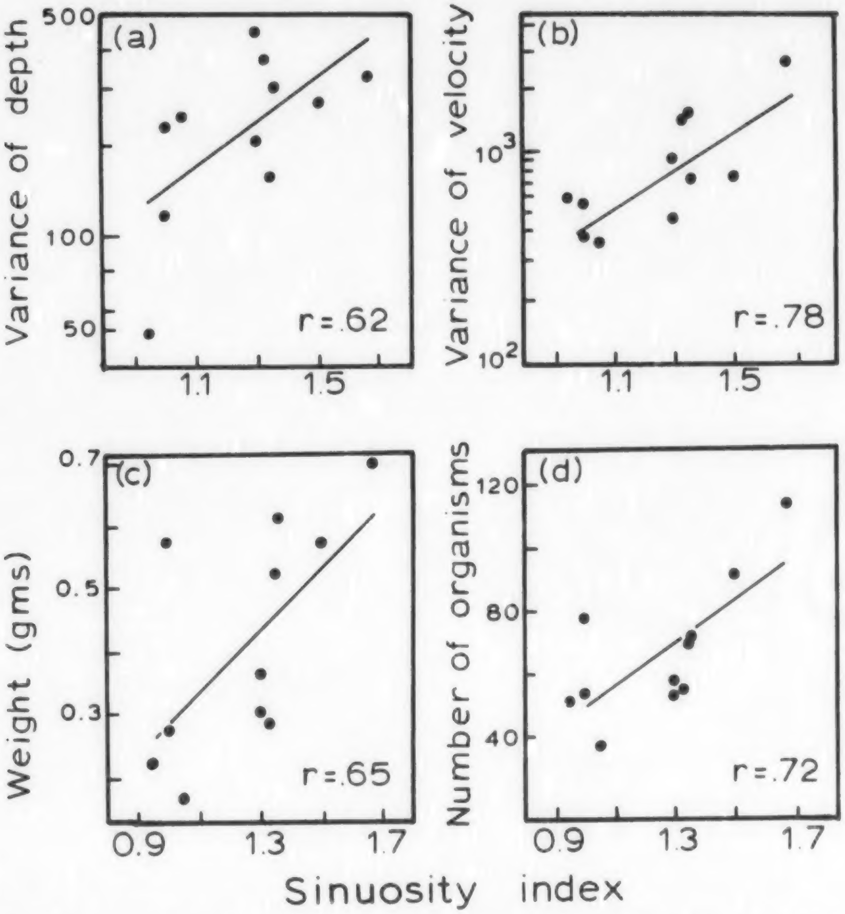

Figure 27. Regressions between sinuosity index and (A) variance of depth between cross sections (expressed as a percentage of mean depth), (B) variance of current velocity (expressed as percentage of the mean), (C) mean drift sample weight, and (D) mean number of organisms per drift sample. (From Zimmer and Bachman 1976).

In the broader perspective of the control of non-point pollution, the studies by Zimmer and Bachman (1976) and Gorman and Karr (1977) have extremely important implications. Millions of dollars spent on preventing sediments from entering streams will have minimal return value in improving the quality of biota if present channelization practices continue to destroy the habitat of stream organisms. High water quality is necessary for fishable streams but insufficient in itself if suitable habitat is not maintained.

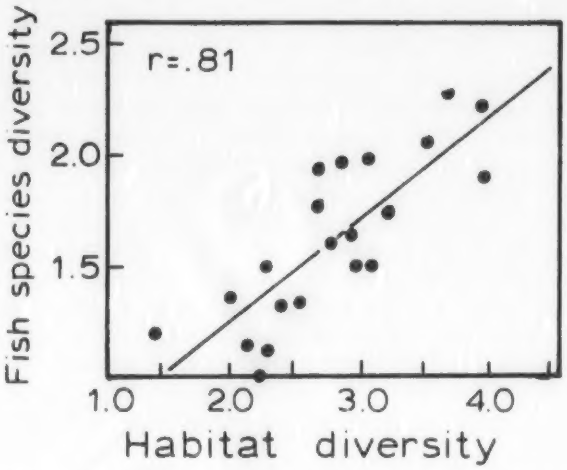

Figure 28. Regression of fish species diversity on habitat diversity. Habitat diversity is calculated from a combination of substrate, depth, and current characteristics (From Gorman and Karr 1977).

CONCLUSIONS

It should be evident from this brief review of selected aspects of the effects of land use on stream biota, that any attempt to improve the quality of those resources must involve a broad based, multi-purpose program. The reasons for this can be best understood by examining a graphical representation of how species are adapted to the physical environment (Figure 29a,b). An organism's physical environment can be represented by a number of different environmental gradients. These gradients might represent factors such as water temperature, water velocity, oxygen concentration, size of substrate, food type, depth of flow and others. For ease of representation only three environmental gradients are plotted. Each organism can survive under a limited range on each gradient, e.g. from 15°C to 25°C on the temperature gradient. With all of these gradients defined for a species, a hypervolume of conditions under which the organism can survive will be defined. For an organism that is a generalist, the range of conditions will be large and in turn the niche volume **is larger** (Figure 29b). For a specialist, the range of conditions is reduced and hence the volume is smaller. In either case a number of environmental conditions must be met before the organism will be able to survive. If only one of the environmental variables is sufficiently altered, the organism will not be able to tolerate the change and will be displaced, regardless of other environmental conditions. On an average, the magnitude of the change must be larger to displace a generalist than a specialist.

Therefore, eliminating only one of the factors detrimental to fish populations or other stream biota will result in very little improvement in these resources. For example, if sediments are prevented from entering streams in agricultural watersheds but vegetation is removed from streambanks, elevated temperatures will probably prevent any substantial increase in the quality of the fish community. Or if sediments and nutrients are prevented from entering streams but channelization is still performed, the lack of suitable habitat will prevent any improvement in fisheries resources. Before substantial improvements in the biota of streams can be obtained, realistic management of nearstream vegetation and stream morphology must be used in conjunction with improved tillage practices. Data presented here suggest that nearstream vegetation may reduce sediment and attached nutrient inputs and temperature fluctuations. Further, a more natural stream morphology may reduce sediment loads and provide suitable habitat for both fish and invertebrates. Data collected in forested watersheds (Hall and Lantz 1969) and in agricultural areas (Karr and Gorman 1975), indicates that these factors acting in concert result in a more productive, diverse, and stable stream biota.

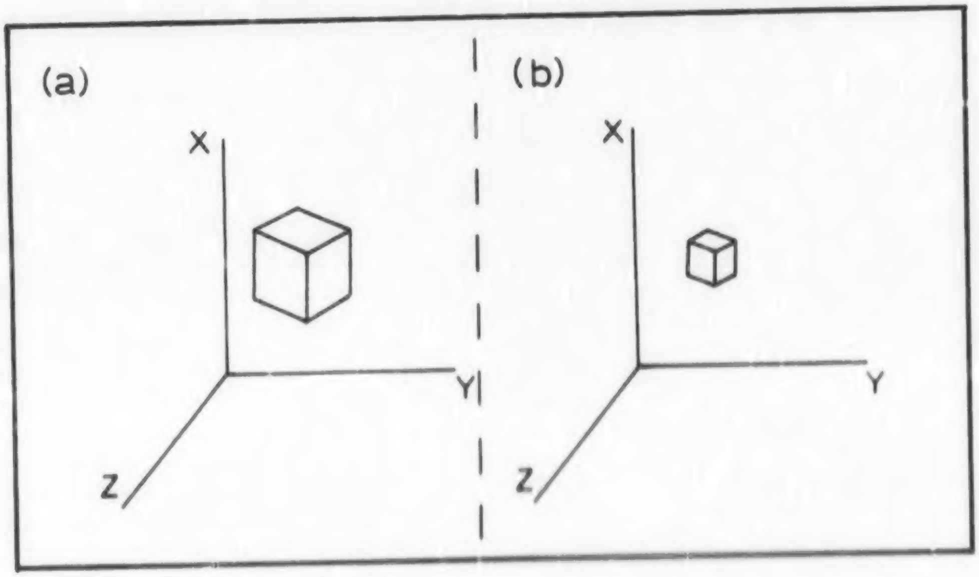

Figure 29. Range on three environmental gradients (X, Y, and Z) under which hypothetical generalist (a) and specialist (b) could exist. Note that the range of conditions under which a generalist can survive is broader than that of a specialist.

SECTION 10

RECREATIONAL BENEFITS OF GREENBELTS

Although space does not permit an extensive evaluation of all possible benefits to recreation from greenbelts, a few of these should at least be mentioned. Maintaining a strip of "natural" vegetation along the upper reaches of streams in agricultural watersheds will provide a substantial amount of habitat suitable for a number of terrestrial game species. The improved cover and forage would result in significant increases in pheasants, dove, quail, rabbits, and many non-game species in these areas (Ferguson et al. 1975). The magnitude of increase could probably be estimated from existing data or a minimal field survey. On larger streams, greenbelts could have a number of significant uses if their development was planned properly, including fishing, hunting, sightseeing, picnicking, camping, nature study and canoeing. A study done by Fleener (1971) found that 96,500 trips and over 384,000 hours were spent in these activities in one year on a greenbelt 30 m wide and 57 miles long on each side of the Platte River in Missouri. Furthermore he found 67% of the people travelled 25 miles or less and 31% travelled only 26-50 miles to get there. These data indicate the potential of greenbelts for not only improving water quality and the stream biota, but also for providing multiple-use recreational areas on larger streams within close proximity to the majority of the people. The latter point is particularly relevant in the present time of rapidly increasing energy costs.

SECTION 11

OTHER ADVANTAGES OF GREENBELTS

This report has addressed several major advantages which might accrue from the use of greenbelts along streams. A number of other potential advantages have not been specifically addressed. Some are mentioned briefly in the following comments.

1. Suspended sediments can cause considerable damage including wear and tear on metal parts wherever machinery contacts flowing water. Reduction in sediment loads with greenbelts can reduce the magnitude of this problem.

2. Changes in water temperature and sediment and nutrient loads can precipitate major shifts in algal communities. These shifts can affect the taste and appearance of water.

3. High water quality and the associated rich biotic communities can reduce the problem of pathogens surviving in water supplies.

4. Frequency and cost of removing sediment from drainage ditches or streams could be decreased by filtering sediments from surface runoff before it reaches the stream bed.

5. Cost for removing the excess turbidity from water used for human consumption is reduced.

6. Flood damage, i.e., the cost of cleaning up the sediment deposited, is reduced.

7. Probability of flooding is reduced due to less clogging of the channel by sediments and because of the more controlled release of runoff.

8. Costs for storage space destroyed by silting in of reservoirs is diminished.

SECTION 12

DISCUSSION AND CONCLUSIONS

Any attempts to understand the dynamics of sediment transport and the biological communities of streams must recognize the interrelationships between water bodies and the land and atmosphere which surrounds them. Rivers are functional parts of much larger landscape units, and they receive most of their individual characteristics from the landscapes of their drainage basin (Fig. 30; Sioli 1975). The channel bottom and suspended solids loads are derived from the landscape and the form of the bed is at least partially determined by the geological history of the surrounding area. The biota of a watershed also determines many of the characteristics of a stream, including the amount of organic matter and the molecular characteristics of that organic matter (Janzen 1974). The complex interplay of biological, geological, chemical, and physical phenomena in both the terrestrial and aquatic environments are of major importance in determining stream characteristics (Hynes 1975, Likens and Bormann 1974).

In an undisturbed watershed both the terrestrial and aquatic environments are in an equilibrium, albeit a dynamic equilibrium. In natural watersheds, drastic fluctuations in water levels are uncommon (unless extremes in rainfall occur). Under most circumstances rainfall is absorbed by the land surface and subsequently released from the soil to the stream over a long period (Hewlett and Nutter 1970). Furthermore, there is little surface runoff from natural watersheds during periods of normal rainfall. Nutrient cycles are "tight" in natural watersheds with very few nutrients being lost to the drainage waters (Likens and Bormann 1974). Under most circumstances the small amounts of nutrients lost from the terrestrial environment are readily assimilated by the biotic communities of the stream. Erosion in this equilibrium state is minimal (Hobbie and Likens 1973).

When man arrives in the area the natural vegetation is removed and instabilities in the terrestrial environment are an inevitable result, especially if conservation practices are not employed. These instabilities have repercussions which affect the aquatic environment and disturb the equilibrium in that section of the biogeocoenoses, to use the European terminology (Sukachev and Dylis 1964) or ecosystem, in the American literature (Tansley 1935). Often, the response is to modify the stream channel to (1) improve drainage of the land surface, and (2) reduce natural bank erosion and other bank instabilities stimulated by the modification of the land surface with the advent of agriculture and urban development. These channelization activities create more instabilities in the aquatic environment. The combined effects of modifications on the land and restructuring of channels result in

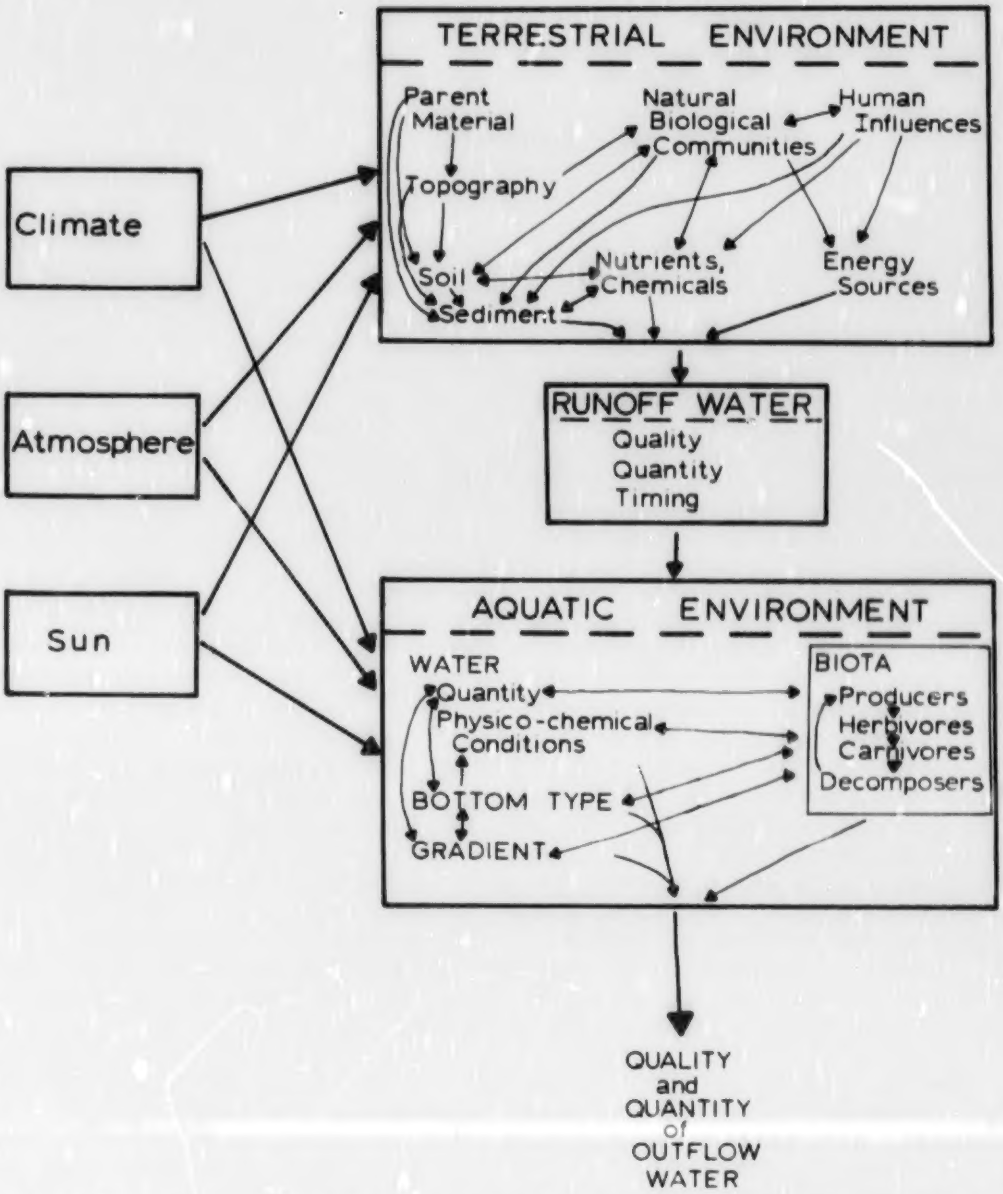
TERRESTRIAL ENVIRONMENT
Parent Material
Topography
Soil
Sediment
Natural Biological Communities
Human Influences
Nutrients, Chemicals
Energy Sources
Climate
Atmosphere
Sun
RUNOFF WATER
Quality
Quantity
Timing
AQUATIC ENVIRONMENT
WATER
Quantity
Physico-chemical Conditions
BOTTOM TYPE
GRADIENT
BIOTA
Producers
Herbivores
Carnivores
Decomposers
QUALITY and QUANTITY of OUTFLOW WATER

Figure 30. General model of the primary factors governing the quality and quantity of outflow water from an ecosystem (From Karr and Gorman 1975).

disequilibria in both the aquatic and terrestrial areas. Readily observed signs of this disequilibrium include:

1. Rapid runoff resulting in drastic fluctuations in the water levels of streams. These include floods during heavy rains and nearly stagnant conditions during dry periods.

2. Large volumes of nutrients and sediments are lost from terrestrial ecosystems to aquatic ecosystems, often over short time periods (Hobbie and Likens 1973, Likens and Bormann 1974).

3. Increased fluctuations in stream temperature (Likens 1970).

4. Increased streambank erosion as the stream attempts to re-establish its equilibrium by forming pools and riffles and meanders (Yang 1971a,b).

5. Decreased diversity and stability in the biotic component of the aquatic ecosystem due to the less stable environment produced by a complex of sediment, nutrient, temperature and stream morphology effects (Margalef 1968, Odum 1969, Karr and Gorman 1975, Gorman and Karr 1977).

If we compare two hypothetical, identical forested watersheds, these patterns can be illustrated in a study of disequilibrium in sediment loads and biotic communities (Table 8). Clearing of the land without conservation activities and channel modifications produces considerable instabilities. If equilibrium is attained in the terrestrial component of the watershed but the streams are channelized, increased sediment loads and major disequilibria in the biotic and abiotic components of the aquatic ecosystem will result.

The natural tendency is for the ecosystem (terrestrial and aquatic) to return to equilibrium by natural successional processes (Margalef 1968, Odum 1969). However, the activities of man--agriculture and construction in the terrestrial area, and channel "maintenance" in the stream--tend to maintain a disequilibrium. Regrettably, this is the situation throughout much of the U. S., especially in the heavy agricultural areas of the Midwest.

Stabilization of the terrestrial environment within the requirements of maintaining an intensive agricultural system is an essential component of achieving water quality. With careful management in fields (i.e., minimum tillage, rotational practices, etc.) and along streams (i.e., greenbelts) effects of the terrestrial disequilibrium can be minimized.

However, major efforts in this area will yield only partial success in achieving water quality goals as long as the present approach to stream management prevails. That is, before major improvements in water quality and stream biota can be realized, the present philosophy of erosion control on the land surface must be combined with a more reasoned approach on the management of stream channels (Table 11). A coordinated management program should, first, reduce sediment input and, second, manage the stream channel to reduce USP. The stream channel will be filled with sediment transported from the land surface if USP control is emphasized first.

TABLE 11. EFFECT OF VARYING "MANAGEMENT PRACTICES" ON EQUILIBRIA OF EQUIVALENT WATERSHEDS. These are best estimates of relative effects for a variety of watershed conditions, including sources and amounts of sediment.

	EFFECT ON EQUILIBRIUM					
	TERRESTRIAL	AQUATIC				
		ABIOTIC		BIOTIC	SUSPENDED SOLIDS LOAD	SOURCE OF SEDIMENT
		TRANSPORT	EROSION			
Natural Watershed	None	None	None	None	Low	-----
Clear Land for Row Crop Agriculture	Major	Major	Minor*	Moderate-Major	Medium	Land Surface
Channelize Stream	None	Major	Major	Major	High	Channel Banks
Clear Land and Channelize Stream	Major	Major	Major	Major	Very High	Equilibrium Between Land Surface and Channel Banks
Best Land Surface Management with Channelization	Low	Major	Major	Major	Medium High	Channel Banks
Best Land Surface and "Natural" Channel	Low	Low	Low	Low	Low-Medium	Equilibrium Between Land and Channel

*Will increase if hydrograph peaks (floods) more severe.

In summary, before the admirable objectives of the Federal Water Pollution Control Act of 1972 (Public Law 92-500)--fishable and swimmable water by 1983--can be attained, it is essential that an equilibrium concept be implemented in the control of non-point source pollution. Furthermore, this philosophy must involve equilibria in both terrestrial and aquatic ecosystems.

We believe this report has demonstrated the value of a perspective which emphasizes the link between terrestrial and aquatic environments and the dynamics of stream behavior. The suggestion that near-stream vegetation along with soil conservation practices and "natural" stream morphology can produce substantial improvements in water quality is supported for areas of intensive agriculture. Furthermore, this management alternative should enhance the quality of fishery resources and provide a variety of recreational benefits. The magnitude of these benefits must, of course, be weighed against the costs (Table 12). Perhaps the techniques of decision theory recently used in studying buffer strips along streams in the field of forestry (Sadier 1970, Gillick and Scott 1975) should be applied. This approach will require substantial new research efforts on a number of questions raised in this paper. These problems must be dealt with at the individual drainage and watershed levels before the environmental and economic value of these management strategies can be fully evaluated.

TABLE 12. COSTS AND BENEFITS OF MORE EFFECTIVE MANAGEMENT OF NEARSTREAM VEGETATION AND CHANNEL MORPHOLOGY. This is not meant to be a comprehensive list. Furthermore, the magnitude of the suggested costs and benefits have not been adequately evaluted.

Costs	Benefits
1. Land taken out of production to maintain a vegetative filter.	1. Reduced sediment, nutrient, and pesticide inputs into streams.
2. Land taken out of production to allow meandering.	2. Increased shading resulting in decreased water temperature; this will alleviate problems associated with release of nutrients from sediments, oxygen carrying capacity, temperature and nutrients in downstream reservoirs, and fewer algal blooms.
3. Reduced drainage rates.	3. Improved habitat for fisheries and terrestrial wildlife.
4. Maintenance of greenbelts.	4. Increased recreational opportunities.
5. Reservoir areas for various pests.	5. Decreased cost of channel construction and maintenance activities since nature will provide the vegetation along streambanks via natural succession and the stream itself will initiate meandering and pool-riffle formation.
6. Need for management of recreational areas.	6. Reduced downstream flooding.
	7. May allow more intensive agriculture with reduced effects on the aquatic ecosystem when best land management practices (i.e. minimum tillage) are not feasible.

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GLOSSARY

Active metabolism--metabolic requirements of an organism undergoing normal activity, such as swimming, feeding, etc.

Allochthonous--Material, generally an energy source such as leaves or insects, which falls into the water from the nearby terrestrial environment.

Angular canopy density--a measure of the ability of vegetation along a channel to shade the water in that stream.

Attached nutrients--elemental materials required by organisms (N, P, K, etc.) that are adsorbed to the surface of sediments.

Autochthonous-material, generally an energy source such as algae or insects, which are produced in the stream.

Autotroph--organisms which obtain their nourishment by oxidizing simple chemical elements such as iron, sulfur, or via photosynthesis.

Benthos--bottom-dwelling organisms in stream, lake, and marine environments.

Biological oxygen demand--the oxygen required to reduce the organic material (e.g. in a water sample). Measure of amount of organic pollution.

Biota--the plant and animal life of a region or period of time.

Buffer strip--a strip of vegetation along a streambank which serves to isolate the channel itself from the primary land use in the region. May be a field border of grass or a strip of forest along the stream channel following clear cutting of forest.

Channel--an open conduit (natural or man-made) in which water flows from a higher to lower point.

Channel gradient (slope)--the incline of a channel which may be expressed as the number of feet of fall per 100 feet of horizontal distance.

Channelization--the process of straightening and deepening a stream along with removal of nearstream vegetation in order to increase the rate of drainage from the land.

Channel morphology--the structural characteristics of a channel including such things as bank slopes, depth, sinuosity, etc. Important in determining runoff rates, channel capacity, sediment carrying ability, biotic diversity, etc.

Chemical oxygen demand--similar to biological oxygen demand defined above but referring to the volume of oxygen-demanding chemical wastes in water.

Coarse particulate organic matter--organic matter in a stream, such as fallen leaves, which is present in large size units; that is, before decomposition or invertebrates have fragmented the material.

Community--An association of interacting populations, commonly defined by their co-occurrence in space.

Community structure--a complex of parameters (species diversity, trophic structure, etc.) which can be used to identify the organizational characteristics of a community.

Cold blooded--an organism whose temperature conforms with the temperature of its environment - "poikilothermic".

Continuity equation--Hydraulic equation resulting from the principle of conservation of mass. For steady flow, the mass of fluid passing all sections in a stream of fluid per unit of time is the same, so that as area of flow decreases, velocity of flow increases.

Critical slope--slope threshold above or below which efficiency of vegetation to remove sediment from flowing water declines rapidly.

Delivery ratio--ratio used to describe the proportion of material eroded from the land surface which actually reaches stream channels, lake beds, or other locations.

Detention time--the time during which water is stored or held by, for example, a PTO terrace before it is released slowly to a nearby channel.

Ecosystem--the totality involved in the plants and animals (biota) plus the physical environment of an area and their interactions.

Environmental gradient--A physical or biological factor varies in its effect over space; e.g., temperature changes as one climbs up a mountain.

Erosion--wearing away of land surface by detachment and transport of soil and rock materials. May occur through action of wind, water, or other agents.

Eutrophication--the accumulation of nutrients in a body of water more rapidly than natural biological processes can accommodate them.

Filter (vegetative)--the use of living vegetation or surface litter to reduce sediment content of flowing water. Results from changing velocity, turbulence, and other characteristics of flowing water.

Flow rate--The volume of water moving past a location per unit time.

Flow retardance--situation when debris or other material in a channel or other area of moving water inhibits the flow of that water.

Food chain--sequence of organisms which depend on each other as sources of food; more or less linear sequence. (see food web)

Food web--complex of organisms with many pathways (food chains) interdigitating from plants to top carnivore.

Fry--recently hatched young of fish.

Greenbelt--Narrow band of vegetation along the channel of a stream. May be either natural assemblage of plant species or a selected species or group of species.

Habitat--the natural environment of an organism.

Habitat diversity--as the number of habitats (pools, riffles; bottom types, etc.) in a reach of stream increases, the habitat diversity of the stream increases. It is important in determining the species diversity of the resident biotic community.

Headwater--the upstream end of a drainage complex; usually considered to be stream orders 1-3.

Heterotroph--organisms which obtain their nourishment from organic matter.

Holistic--the philosophy that for complete description of a system the behavior of the individual components must be combined with knowledge of the components joined as units; very simply, the whole is equal to more than the sum of its parts.

Infiltration filter--area of vegetation where nutrients and/or sediment are removed as water infiltrates down through the soil profile; there is no surface runoff out of such an area.

Invertebrate drift--aquatic invertebrates which release their hold or are torn loose from a substrate and move downstream with the moving water.

Jackson Turbidity Unit (JTU)--see turbidity.

Meander--the winding of a stream channel

Metabolism--the totality of chemical activity in a plant or animal which results in the provision of energy and nutrients to the organism.

Microflora--microscopic organisms such as bacteria, fungi, and other groups in a biotic community. Frequently used to refer to those organisms colonizing decomposing organic matter.

Nursery area--the region where immature fish initiate growth and development.

Nutrient--a substance required by an organism for normal growth and maintenance.

Organic matter--materials which are produced by living organisms which contain carbon and are not in a completely oxidized condition.

Opercular cavity--the region under the gill cover (or opercle) of a fish where the gills and gill arches are located.

Overland flow--water flowing on the surface of the land; in contrast with channel flow or underground movement of water.

Parallel tile outlet terrace (PTO terrace)--a system of low terraces constructed to impede the runoff of water from the land surface while providing for a slow release of water through a tile system; results in improved water quality by reducing sediments carried to stream channels.

Periphyton--The plants and animals attached or clinging to stems and leaves of rooted plants or other surfaces projecting above the bottom of a body of water.

Productivity--rate at which energy or nutrients are assimilated by an individual, population or community (amount per unit time). Important to distinguish between net production which is the rate of accumulation in a system and gross production which involves both accumulation and the amount metabolized in the maintenance of the organisms. Primary productivity is productivity of plants, while secondary productivity is productivity of animals.

Reductionist--the philosophy which suggests that a complex system can be fully described by decomposing it into successively smaller components and describing their behavior.

Roughness factor (n)--Measure of the irregularity in a drainage channel which will reduce velocity of flow of water in the channel.

Salmonids--fishes in the family Salmonidae, including trout and salmon.

Sediment--fragmentary material that is transported by water or air or is accumulated in beds by natural processes.

Sediment deposition--the placement of sediment in a location after its movement by wind, water or other geological agents.

Sediment load--all particulate matter carried or transported by water.

Sediment trap--a specifically constructed area to reduce flow velocity of water thereby reducing its sediment carrying capacity.

Shallow channel flow--water flowing in a channel when the depth of the water does not exceed the herbaceous vegetation in the channel.

Sinuosity--the ratio of channel length to down-valley distance. That is, an index to the amount of meandering by a stream.

Social hierarchy--a social organization among animals in which dominance position within the group determines use of available resources.

Spawning--the act of laying and fertilization of eggs in fishes and shellfishes, especially.

Spawning grounds--area or location where fish reproduce (lay eggs). Typically characterized by specific bottom type, current, etc. for each species.

Species diversity--a measure of the complexity of a community, which may be simply the number of species (species richness) or a more complex index utilizing information on number of species and their relative abundances.

Standard metabolism--metabolic requirements of an organism for maintaining normal physiological functions (e.g. heartbeat, muscle tone, respiration, etc.).

Streambank--the sides of a channel which are exposed during most normal flow periods.

Stream order--A method for numbering streams as part of a drainage network. The smallest stream channel is first order. A second order stream is reached when two first order channels join, etc.

Subsurface runoff--underground movement of water either through natural drainage pathways or through tile systems. Subsurface runoff may or may not reach an open channel.

Succession--the process of replacement of one biotic community by another. Each successive community changes the physical and biotic environment by its presence.

Surface litter--plant debris deposited on the soil surface which helps to protect that surface from disturbance by raindrop impact or overland flow.

Surface runoff--movement of water overland until it reaches a channel.

Suspended sediment--fine particulate material which remains in suspension and without contact with the channel bottom.

Tile line--an underground conduit installed by man to facilitate drainage of water from an area and thereby lower the water table.

Transfer coefficient--amount of material moved from a system component to another component relative to the amount in the donor compartment usually expressed as a ratio.

Turbidity--condition of water resulting from the presence of suspended material. Typically expressed in Jackson Turbidity Units, a measure of interference with light transmission.

Unit stream power (USP)--the energy available in flowing water; a function of the slope and velocity of the channel in which the water is flowing.

Universal soil loss equation (USLE)--equation developed by agricultural scientists to predict the amount of soil eroded from a land area.